UNIVERSITY OF LIVERPOOL

Underwater Communication using Electromagnetic waves

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Doctor of Philosophy
by
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Abstract

This project was to investigate the EM waves for transmission in seawater with a varied frequency from about 1 MHz up to 40 MHz. Trials were carried out in the laboratory tank, the Albert Dock and the Loch Linnhe. Standalone transmitter and receiver units were constructed for performing the experimental trials. A receiver is used to pick up the signal from the transmitter and the signal was analysed using a spectrum analyser. Frequency can be varied outside the transmitter from a lap top by using an optical fiber. Different types of antennae were built and tried in the experiments. In the Albert Dock, the results have shown that EM waves in the range of 1 to 5 MHz is possible to propagate about 100m using a 30W power amplifier.

A new antenna design was developed and investigated in the laboratory tank. Results have shown that there is about 30dB gained by implementing the new antenna design. The signal strength can be further improved by 10 dB when the antenna and the signal generator were matched at 10MHz.

In the near field, EM waves suffer from high attenuation in seawater but have a low attenuation in the far field. This is due to the generation of EM waves by dipole oscillations of the water molecules within the antenna field which can be used to explain results obtained from trials.

Acknowledgements

My deepest gratitude goes to Professor J. Lucas for his invaluable advice and comments inspiring me throughout my research. Also, his continued supervision, encouragement, patience and support were indispensable. The researching period became enjoyable when working with him.

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Contents

Chapter 1

Introduction

Project introduction will be discussed. Next, the aims and objectives of the research activities will be stated for the full project. Finally, the thesis chapter structure will be specified.

1.1 Project introduction

The extremely low frequency (ELF) or very low frequency (VLF) electromagnetic (EM) waves limited by low data rate for transmission, the large physical size of antennae and the requirement of high power consumption of the transmitter. Therefore, this project is focusing on investigating the EM waves in the range of 1 to 20MHz propagation in seawater. Trials were performed in the laboratory tank, the Albert Dock and the Loch Linnhe. The open real marine area trials were vital as to eliminate the reflections of the boundaries in the tank. The required instruments were built according to the test environment. Experimental equipment included transmitters, receivers, antennae, signal generator, amplifier and fibre optics communications. The experimental equipment used was almost the same for the laboratory tank and real marine environment except that the transmitter and related components were rugged used to compensate for the severe environment of sea.

Underwater communication is useful for offshore oil industries, diver to diver communication, navigation for ships, mapping of the seabed and detection of objects [1]. Using wire communication in underwater is costly and has limited applications. This is because the maintenance and making of wires are expensive in this severe environment. Therefore, wireless communication in underwater is essential. To achieve this, standalone transmitter and receiver without cables between them are used. Transmission of signal can be done by optical, acoustic or electromagnetic waves propagation. Acoustic system is common but there are some disadvantages such as multi-path propagation seriously affects the reliability of the system especially in shallow sea, the data rate for transmission is slow and waves are reflected by large objects in the sea. Optical system suffers from scattering rather than attenuation. In seawater, there are a lot of micro particles so it is not suitable for light to transmit. EM waves for transmission are an alternative way to do the job, but seawater is highly conductive (conductivity in the range of 4 S/m) so EM waves will be highly attenuated while propagating in seawater except for the medium radio frequency in extremely low frequency range. Also the conductivity varies with temperature in the medium so the optimum frequency for transmission in seawater is shifted in accordance with the temperature. To increase the efficiency of the system, the transmitter should have the ability to tune over a range of frequencies. Therefore, the frequency for transmission can be tuned according to the temperature in the seawater to obtain maximum efficiency for the whole system. The transmitter and receiver were constructed to investigate different frequencies (1 to 20 MHz) for transmission in seawater to find out what range of frequencies has the higher efficiency. Also the antennae used to launch and receive the EM waves are also critical. The design of the antennae will also affect the performance of the whole system. Therefore, several types of antennae were built and their performances were investigated.

1.2 Project aims

1. To design an antenna that can be used in seawater with the highest output power for practical use without further use of a receiving amplifier.
2. Different types of antennae will be constructed. Then find out which type of antennae has better performance in seawater than the rest.
3. Design a standalone transmitter and receiver system suitable for underwater communication.
4. Construct a transmitter that has the ability to tune its frequencies instantly and remotely by user without actually retrieving the transmitter.
5. Construct a robust underwater receiver to receive EM waves at frequencies from 1 to 20 MHz.
6. Undertake trials in the laboratory water tank and the real marine environment.
7. Design, analysis and implementation of various modulation schemes are compared for transmission.
8. Perform texts, if possible voices and pictures transmission in seawater both in laboratory water tank and Liverpool marine.

1.3 Project objectives

1. To design an antenna so that it will have an optimum performance in seawater.
2. Design an amplifier to be used in the transmitter.
3. Construct transmitter and receiver system.
4. Record the signal strength (dBm) with distance by using the spectrum analyzer. From the results, the signal strength against distance graph is plotted.
5. Record the impedance of the antennae in seawater of different conductivity for a range of frequencies.

6. Matching circuit for both transmitter and receiver. So the power efficiency of the whole system will be increased.
7. Modulation and demodulation of the signal.

1.4 Thesis structure

Chapter 2 is about the literature review. It gives some background information about the wire communication and wireless radio communication including analog and digital communication.

In Chapter 3, the basic theory of the antenna, EM waves and the classic Debye's theory. EM waves are introduced and their relevant information is given. It is important to have the basic knowledge about the antenna and the transmission line. Because the efficiency of power transmission from the source to the antenna depends on the transmission line and the signal strength for transmission depends on the design of the antenna and the medium that the EM waves propagate.

Chapter 4 contains the procedures in the experiments performed in the laboratory tank, the Albert Dock and Loch Linnhe. Independent observers may follow the experimental procedures to repeat any experiments again. The experiments should be repeatable and the results should be similar or only slightly in difference due to the conductivity of the seawater may be varied according to the temperature.

In Chapter 5, experimental results are shown and analysed. The results are discussed and explained. The impedance of antennae used in seawater are recorded and presented. Graphs of VSWR against frequencies are also shown in this chapter. The experimental results of the signal strength against distance of different types of antenna with varied frequencies for transmission are presented.

In Chapter 6, to conclude results has been obtained in the project. A summary of the whole project is given. Recommendations for future work in this project are discussed.

All the references used in this project are listed in Chapter 7. It includes books, websites and publications used in the thesis.

Chapter 2

Basic communication principles

Literature review of underwater communication will be discussed. Then basic communication principles will be introduced to give some information on how a communication system works. The analogue and digital communication systems are defined, explained and compared. Some common modulation schemes for analogue and digital communication are explained with examples. Finally, some communication channels are discussed together with their applications.

2.1 Literature review

The electromagnetic (EM) and acoustic communication in underwater conditions will be discussed and will highlight the advantages and disadvantages of both technologies.

2.1.1 Electromagnetic waves communication in underwater

Electromagnetic waves at extremely low frequency (ELF) and very low frequency (VLF) have been used for underwater communication [2] [3]. An ELF at 45Hz is emitted from an antenna placed on or near surface of the seabed and received by a submerged submarine for subsea communications has been suggested in the past [2]. Also a project Sanguine/Seafarer had a similar idea of using ELF in the range of 30 to 100Hz for transmission [3]. The path for EM waves to propagate is from the earth to the atmosphere and back into the sea and a diagram of the propagation path is shown in figure 2.1.

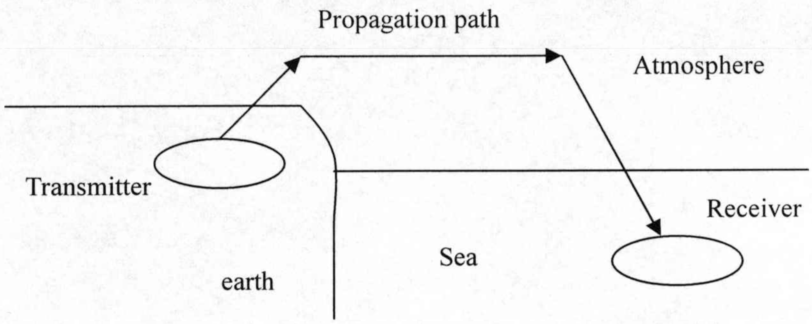


Figure 2.1 The propagation path of the ELF communication system

With both the transmitter and receiver submerged in the sea, the propagation path of EM waves are suggested as being from the dipole transmitter through the sea to the surface and travel through air along the surface, then back into the sea to the dipole receiver [4]. A simple diagram of the propagation path is shown in figure 2.2.

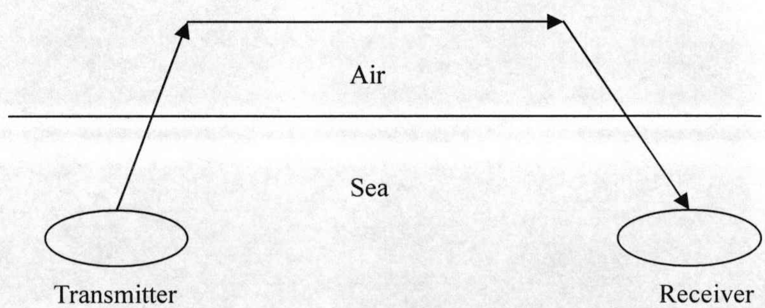


Figure 2.2 The propagation path of two submerged dipoles

These two EM waves propagation paths shown in figures 2.1 and 2.2 may be the technique of the transmission of EM waves from the transmitter to the receiver [5]. The design of antennae for communication in underwater is vital and important. The reason behind this is to prevent the antennae from affecting the performance and efficiency of the whole communication system. Some work on the air to sea interface with certain types of antenna configuration was done in order to investigate the behaviour of underwater antennae for receiving EM waves [6]. Simple antennae such as dipoles, loops and electrodes were commonly applied in underwater communication.

There are many disadvantages of using ELF. Firstly, at ELF, the attenuation of EM waves in seawater is low but the atmospheric noise created by lightning strikes is large and the noise is impulsive rather than Gaussian [2]. Also factors of the time of day, location and season determine the atmospheric noise level, thus the design of the receiver is more complicated.

Secondly, an efficient antenna at ELF range is large in physical size. Therefore, losing the ability of mobilization and the communication system is one direction only (simplex) not in both directions (duplex). For example, transmitter with large antenna is stationary on the earth while the receiver on the submarine is mobile and the communication link is from the transmitter to the receiver only and cannot be reversed.

Thirdly, the power consumption of the ELF system is huge to overcome the transmission loss through different media and the launching of the large antenna. Power amplifiers with large amplification are expensive so the whole ELF system may be costing too much to be deployed.

Finally, the transmission data rate is slow for ELF. It may not meet the real time applications of today's need.

Other than EM waves at ELF, EM pulses excited by antennae and propagation through conductive medium were also studied and some solutions were given [7] [8] [9]. Similarly, a pulse consists of a wide frequency band. When propagating in seawater, different frequencies will have different attenuation. So the pulse received at the receiver is deformed from the original shape.

2.1.2 Recent technology of underwater acoustic communication

The system and reliability of underwater acoustic communication has advanced a lot recently. The speed of processing has increased dramatically in computation which led to many solutions to improve underwater acoustic communication. With the implementation of different schemes of digital communication, the speed and reliability for transmission has been increased. Application of the error correction coding can reduce the system error probability and achieve coding gains with a lower bandwidth expansion but the computational complexity of the system may be increased [10].

The frequency for transmission is varied for different range because acoustic attenuation increases with distance and the multipath formation is governed by the channel geometry. So three kind of ranges at certain frequency for transmission, short range system for several tens of meters at hundred kHz, medium range system for several kilometres at ten kHz and long range system in deep water for several tens of kilometre at few kHz.

The ocean acoustic channel characteristics are carefully considered when designing an underwater acoustic communication system for a unique application. During acoustic transmission, fluctuations are induced by internal waves, turbulence, temperature gradients, density stratification, and related phenomena causing local perturbations in the sound speed. The received waveforms are suffered temporal, spatial and frequency dependent fluctuations by the diffractive and refractive effects of the regular wave fronts and the fluctuations induced while transmitting. Also multipath exists in most underwater propagation geometries from the transmitter to the receiver [10].

Ambient noise is the key factor for controlling the power of transmitter because the signal received at the receiver must be higher than the ambient noise so that data can be recognised. The signal to noise ratio (SNR) is power ratio between a signal and background noise which is a term to show the quality of the signal received. The higher SNR of the system, the better it is. Inshore environments and marine worksites are usually higher ambient noise level than deep ocean environment. Most communication systems assume the ambient noise is additive and Gaussian but in some warm shallow water regions, it is impulsive and highly non-Gaussian because the domination of the noise signal generated by the snapping shrimp [11].

The time varying multipath propagation is the major problem of underwater acoustic communication and it exists nearly all the time. The difficulty of synchronization of the transmitter and the receiver increases due to the time varying multipath. This is because the arrival times of the waveforms to the receiver are different after going through multipath propagation and sometimes, the first arrival may undergo the longest path and arrives late or even disappears entirely.

The receiver of underwater acoustic communication requires complex structures to improve the speed, reliability and robustness of the system. The computational time is increased with the complexity of the receiver containing a processing microprocessor. When the computational load is too high, it will take a long time for the microprocessor to deal with the data. Thus the real time implementation of the underwater acoustic communication is reduced [12].

Summing all factors in acoustic underwater communication, those disadvantages are fading, extended time varying multipath propagation for medium range in shallow water, bandwidth limited, the speed for transmission is confined and the high complexity of the receiver precluding the real time implementation. The needs of many underwater applications may not be able to be met by acoustic system technology. The research is continuing to improve the system of acoustic underwater communication. At the same time, engineers are looking for an alternative method to compensate the deficiency of acoustic wave by jointly investigating electromagnetic waves. The interaction of acoustic waves of sound range and low frequency electromagnetic waves under their jointly propagation in conducting marine medium are considered [13].

2.2 Introduction of communication system

A modern society development is highly dependent on communications. In a communication system, information is transmitted from the source to the receiver through a communication channel. A simple communication system block diagram is shown in figure 2.3.

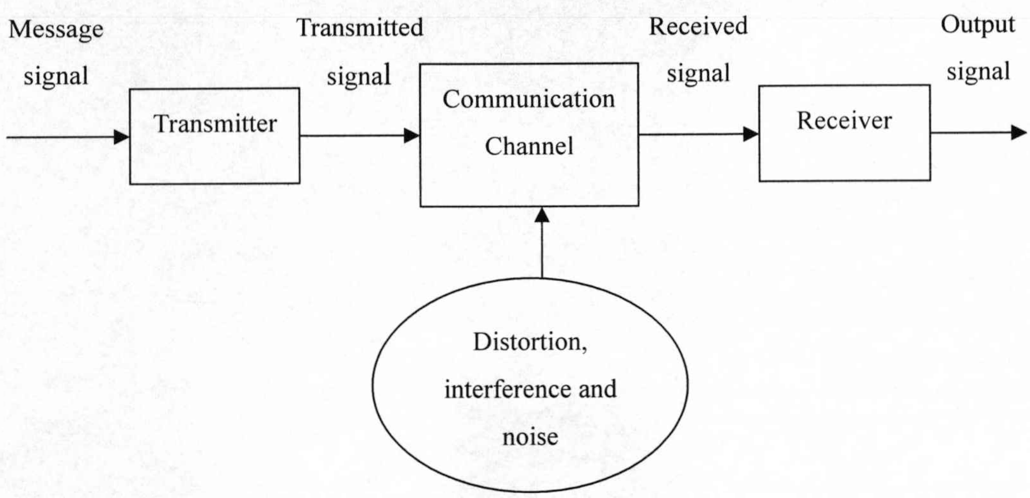


Figure 2.3 The block diagram of a communication system [14].

Signals can be electric or electromagnetic representations of data. Transmitter is used to couple the message signal to the channel. Receiver is used to extracts the desired message signal.

2.3 Transmission protocols

The communication system can be simplex or duplex. For a simplex communication system, data travel in one direction only from one transmitter to one (or more) receiver. Examples include radio broadcasting, television broadcasting, paging services and telemetry. For a duplex communication system, data travel in both directions which is divided into half duplex and full duplex. Half duplex communication means data can travel in either direction, but not at the same time. Walkie-talkie is a good example of half duplex wireless voice communication between two locations. It is a device that can be used as a transmitter or receiver (transceiver). In full duplex communication, data travel both directions simultaneously. Mobile phone is one of the examples. A simple diagram of the communication systems is shown in figure 2.4.

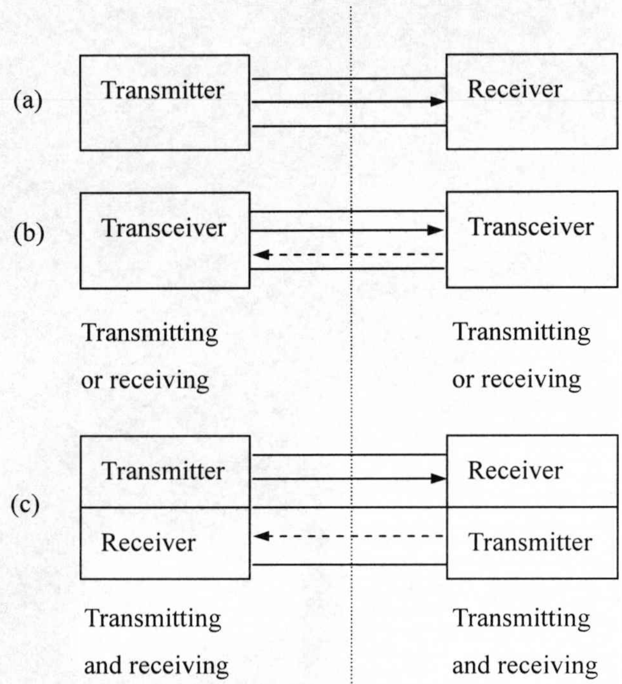


Figure 2.4 Communication systems: (a) simplex; (b) half duplex; (c) full duplex [15].

2.4 Analogue and digital communication

The message signal used may be analogue or digital. For analogue communications, the message signal is analogue and has continuous time and amplitude. For digital communications, the message signals are digital and are discrete symbols with a finite number of values and time.

When analogue and digital systems are compared, it is generally found that digital systems have the advantages as follows [15]:

1. Being cheaper in constructing the signal processing circuit due to the advancing semiconductor technology.
2. Better noise immunity as the number of errors in the received data are small even in the presence of a significant noise level in the receiver.
3. Better security and integrity can be implemented through the data encryption on the information bit stream
4. More modulation schemes
5. Higher flexibility due to the signal processing part of it can be reconfigured by editing the software instead of changing the hardware.
6. Errors can be detected and even corrected by introducing different type of coding techniques

The disadvantages of digital systems are as follows:

1. Require a larger bandwidth.
2. Transmitter and receiver are more complex.
3. An irreversible process of quantization distortion is introduced when the analogue signal is converted to digital signal before transmission (It can be improved by increasing the quantization levels which result in increasing the bandwidth and inter-symbol interference.)

2.5 Modulation and demodulation

Modulation is the process of encoding the message with a carrier wave to meet a particular application. The message signal after modulated will be sent from the transmitter to the receiver and then demodulated at the receiver to extract the original message signal from the carrier signal. The demodulation is the reverse process of modulation which is designed to separate the message signal from the carrier signal. The benefits of using modulation scheme are for ease of radiation transmission by an antenna by increasing the carrier frequency, to reduce the noise and interference by introducing wider bandwidth of the carrier than the message called wideband noise reduction and for simultaneous transmission of several signals without interference is done by multiplexing which has frequency division multiplexing and time division multiplexing. Frequency division multiplexing uses multiple message signals modulated with different carrier frequency for transmitting and were separated with a bank of filters and demodulated at the receiver. Time division multiplexing uses pulse modulation to combine samples of different signals in a definite time sequence. The clock at the transmitter and receiver must be synchronised [16].

In modulation, the amplitude, frequency or phase of a carrier signal is varied according to the amplitude of the message signal. There are mainly three types of modulations, amplitude modulation, frequency modulation and phase modulation. They can be applied to analogue or digital modulation.

2.6 Coding

Coding is used to improve the fidelity in communication systems by introducing some symbol with the message when the information is digital. Encoding is the process of transforming a digital message into a new sequence of symbols. Decoding is to convert the encoded signal back to the original message. Introducing the coding will increase the bandwidth usage but the advantages are to improve the fidelity of the signal and may have the ability to correct the errors which is introduced during communication channel and can be applied in analogue communication using the analogue to digital conversion such as pulse code modulation [16].

2.7 Analogue communication

Two common types of analogue communication are amplitude modulation large carrier (AM) and frequency modulation (FM) in radio broadcasting. AM will be discussed here. Let us consider a message signal m(t) is mixed with a carrier frequency $\cos\omega_c t$ and the modulated signal is Φ_{AM},

$$\Phi_{AM} = A\cos\omega_c t + m(\mathrm{t})\cos\omega_c t \tag{2.1}$$

A simple block diagram of generation of AM signal is shown in figure 2.5.

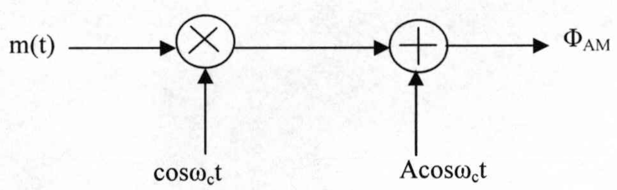


Figure 2.5 A block diagram of AM generation.

To demodulate the AM signal, the received signal Φ_{AM} is mixed with carrier frequency $\cos\omega_c t$. So the demodulated signal is,

$$\begin{aligned} \text{Demodulated signal} &= \Phi_{AM}\cos\omega_c t \qquad (2.2) \\ &= (A + m(\mathrm{t}))\cos^2\omega_c t \\ &= 0.5(A + m(\mathrm{t}))(1+\cos 2\omega_c t) \\ &= 0.5[m(\mathrm{t}) + A + A\cos 2\omega_c t + m(\mathrm{t})\cos 2\omega_c t] \end{aligned}$$

After passing through the low pass filter, the message signal will be recovered with half of the original amplitude. A block diagram of the demodulation is shown in figure 2.6.

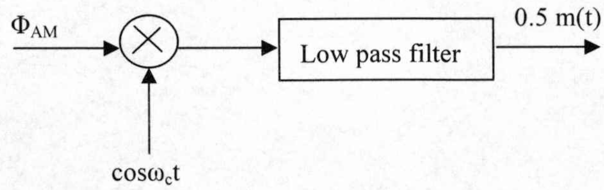


Figure 2.6 A block diagram of AM demodulation.

The advantage of using AM is the demodulation circuit very simple and is non-coherent. Thus, the receiver is low cost. An envelope detector can be used as a receiver which can be constructed using only a diode, capacitor (C) and resistor (R), as shown in figure 2.7. In figure 2.8, $V_i(t)$ is the received signal and the demodulated signal after the envelope detector is $V_o(t)$. When the input signal waveform across the circuit on the positive cycle, the input signal charges the capacitor. When the voltage of the input signal is below the maximum voltage stored in the capacitor, the capacitor starts to discharge but the diode blocked the current goes back so it can be discharged through the resistor with a time constant RC until the input voltage of the waveform is higher than the peak voltage stored in the capacitor in the positive cycle then it charges up again. This process repeats again and again. If the time constant RC is too large, the envelope detector may miss some positive half-cycles of the carrier and thus can not reproduce the envelope correctly. If the time constant RC is too small, a very ragged waveform will be produced and losing efficiency. Thus, the time constant should be adjusted so that the magnitude of the slope of the envelope smaller than the exponential discharge rate of the RC [17].

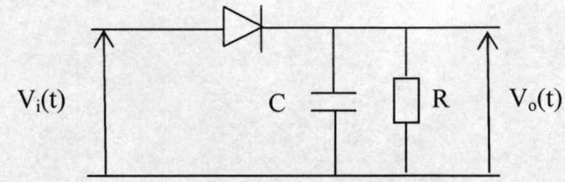


Figure 2.7 An envelope detector.

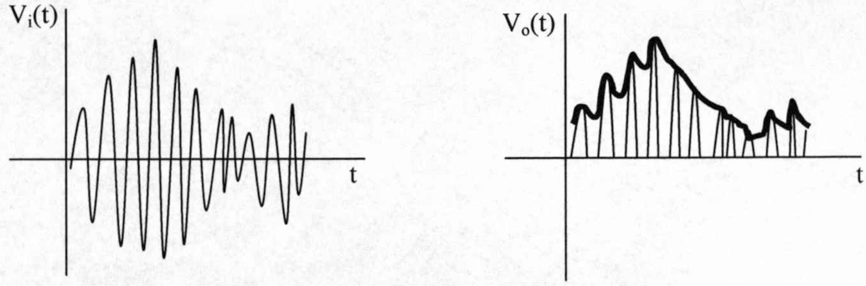


Figure 2.8 (a) Received signal; (b) Signal after demodulated by an envelope detector.

If the message signal is over-modulated, then it can not be recovered by the envelope detector. A modulation index is used to determine if the signal is over-modulated or not and is defined as [14]:

$$\textit{modulation index} = \frac{\textit{peak value } m(t)}{\textit{peak carrier amplitude}} \tag{2.3}$$

When the modulation index is smaller or equal to 1 then the modulated signal can be recovered by envelope detector. If the modulation index is larger than 1 (over-modulated), then coherent demodulation need to be introduced to demodulate the over-modulated signal.

A superheterodyne receiver is commonly used for receiving the radio broadcasting AM and the block diagram of it is shown in figure 2.9. It consists of a radio frequency (RF) section, a mixer, an intermediate frequency (IF) section, an envelope detector, an audio amplifier and a speaker. It performs the tasks such as carrier frequency tuning for selecting the desired signal and to separate the desired signal from other modulated signals by filtering [18]. The modulated signal is received by the antenna and amplified. The RF section is tuned to the carrier frequency of the modulated signal. The mixer translates the carrier frequency (f_c) to a fixed IF frequency (f_{IF}) with a local oscillator (f_{LO}) with $f_{LO} = f_c + f_{IF}$. The IF section provides most of the selectivity and amplification in the receiver. Then the message signal is recovered by envelope detector. Finally, the message signal is amplified and then converted to sound by the speaker. One problem of this design is image signal formed from an unwanted carrier frequency. When the frequency of two signals with the difference of twice the IF frequency simultaneously picked up by the receiver, the image interference occurs from the unwanted signal. This can be cured by introducing selective stages in RF section to suppress the image signal.

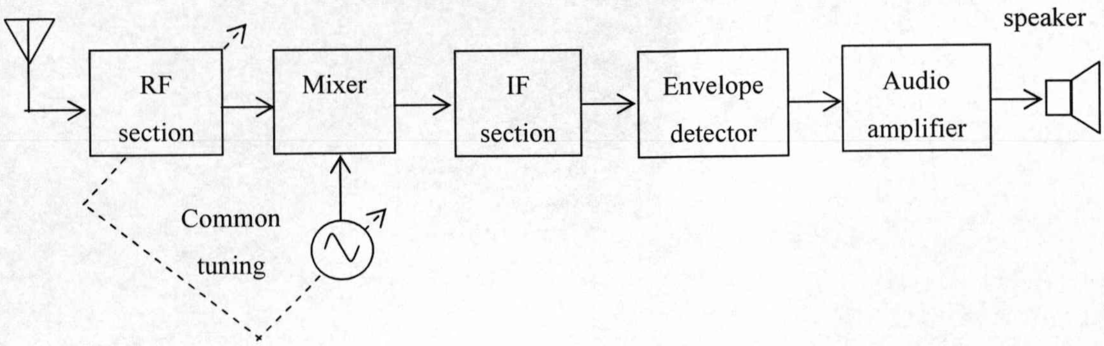


Figure 2.9 The basic elements of the superheterodyne receiver [18].

2.8 Digital communication

Analogue communication is being replaced by digital communication. In the future, the digital communication will become the major part of communication while analogue will become minor part of it. In digital communication, the messages are assumed to be digital and considered as in binary form which contains "1" and "0". For the ease of radiation, modulation also applied in digital communication. Amplitude shift keying (ASK), frequency shift keying (FSK) and phase shift keying (PSK) are used. ASK, FSK and PSK modulation are shown in figure 2.10 when a baseband signal $m(t)$ modulated with a carrier frequency $\cos\omega_c t$. ASK is sending a modulated signal at "1" and nothing at "0", so it is similar to turning on and off to represent "0" and "1". For FSK, there are two carrier frequencies, one is $\cos\omega_{c0}t$ and the other one is $\cos\omega_{c1}t$. In PSK, "0" is transmitted by $A\cos\omega_c t$ and "1" is transmitted by $-A\cos\omega_c t$. [14].

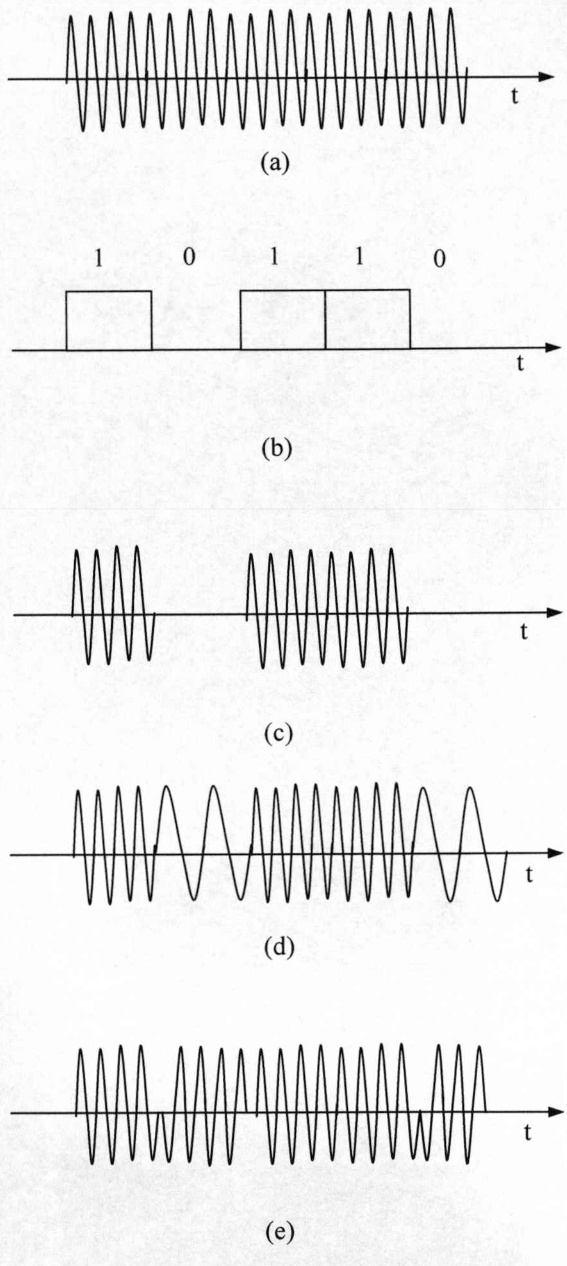


Figure 2.10 (a)Carrier frequency; (b)Baseband signal; (c)ASK; (d)FSK; (d)PSK

The demodulation of a digital modulated signal is similar to the analogue modulated signals. Both ASK and FSK can be demodulated by using non-coherent method so will be discussed while PSK required coherent demodulation. ASK can be demodulated by the envelope detector. For the demodulation of FSK, a matched filter had to be added before the envelope detector according to the carrier frequency ω_{c0} and ω_{c1}. The demodulation block diagram of FSK is shown in figure 2.11. Then the output of the envelope detector will be sampled and compared. When "1" is transmitted, it will pass through the matched bandpass filter of ω_{c1} before being detected by the envelope detector. The envelope detector 0 will not have any signal if the matched filter designed and worked properly. Therefore, at the comparison stage, the signal of the output of envelope detector 1 will be higher than the envelope detector 0 and "1" is decided at the receiver. For detecting the "0", it is the same process but reversed.

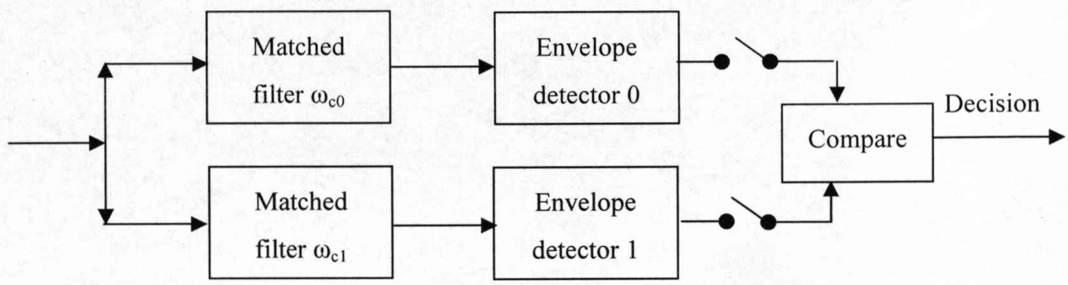


Figure 2.11 The demodulation block diagram of FSK [14].

2.9 Communication channel

The communication channel is the physical medium between two points. Distortion, interference and noise may be added to the transmitted signal in the channel. Communication channels can be classified into closed and open media. In closed media, the transmitter and receiver is physically connected for communication. Coaxial cables, wire pair, optical fibre and metallic waveguide are the closed media commonly used today. Radio broadcasting and satellite communication are two examples of the communication in open media. Open and closed media have their own distinct features, so they can be applied to different circumstances according to their features.

2.9.1 Twisted wire pairs

Wire pairs are made from copper and insulated with plastics. A simple drawing of two conductors insulated individually and encapsulated inside a plastic is shown in figure 2.12. The disadvantages of it are limited bandwidth, crosstalk between pairs and interference noise from radio transmission.

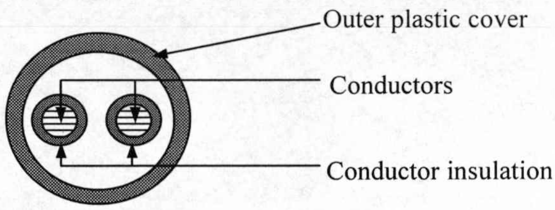


Figure 2.12 Wire pairs

2.9.2 Coaxial cable

Coaxial cables are concentric conductors separated by an insulator. The performance of it is depending on the size and conductivity of the inner, outer conductors and the dielectric in the cable. It is suitable for low frequencies and low data rate transmission because the attenuation of coaxial cables increases with frequency. One problem of coaxial cable is flexible but repeated bending can cause degradation through fatiguing of both the conductors and the insulators [19]. The outer conductor of the coaxial cable is usually earthed so it is shielded in which will not suffer from radiation losses. Mostly it will be used in short distance communication. A simple diagram of a coaxial cable is shown in figure 2.13.

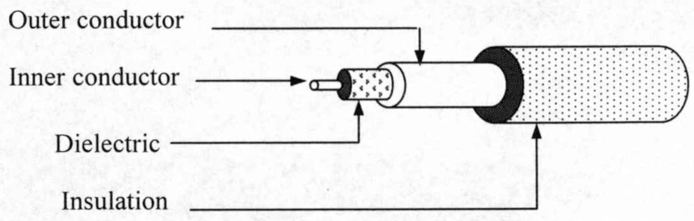


Figure 2.13 A coaxial cable

2.9.3 Optical fibre

Optical fibre is a type of waveguide to guide waves in distinct patterns. There are mainly three types of optical fibre, mono-mode stepped index, multi-mode stepped index and multi-mode graded index fibre. The structure, refractive index profiles and the propagation along the optical fibre are shown in figure 2.14 [20].

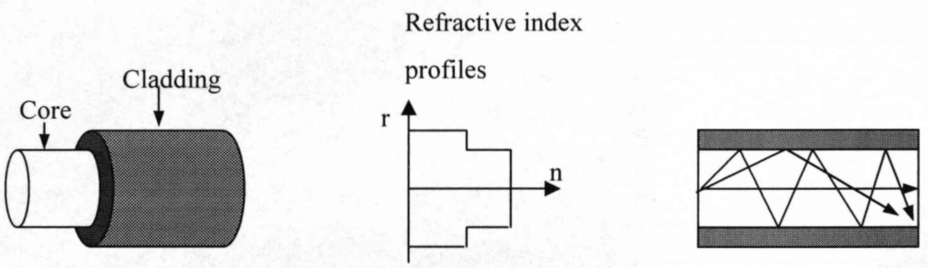


Figure 2.14 (a) multi-mode stepped index optical fibre

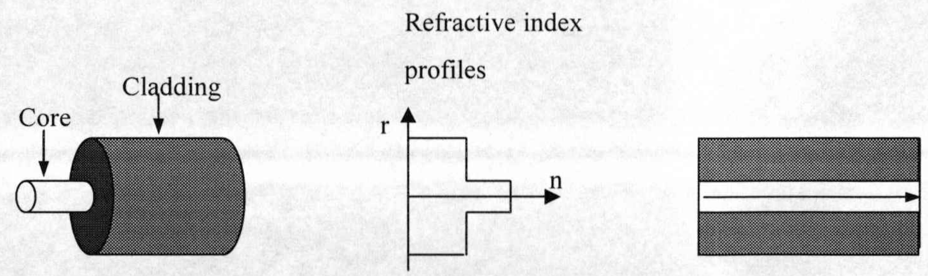


Figure 2.14 (b) mono-mode stepped index optical fibre

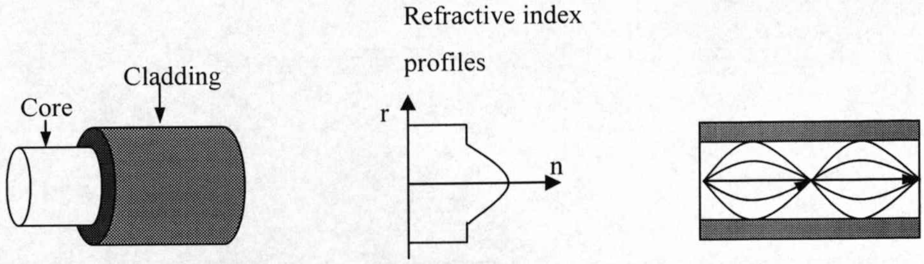


Figure 2.14 (c) multi-mode graded index optical fibre

The transmission of light along the fibre is established by the total internal reflection. The critical angle is depending on the refractive index of the core and the cladding. The critical angle is calculated by:

$$\sin\theta_c = \frac{n_2}{n_1} \quad (n_1 > n_2) \tag{2.4}$$

where n_2 is the refractive index of the cladding and n_1 is the refractive index of the core.

When the light travelling inside the fibre is larger than the critical angle then repeated total internal reflections occur for propagating of light along the core.

In the transmitter, light sources used in optical fibre communication are mainly either Laser (Light Amplification by Stimulated Emission of Radiation) which produces coherent light or light emitting diodes (LED) which produce incoherent light depending on the application. Laser is stimulated emission and must be above the threshold current for operating in an efficient way. LED is spontaneous emission and the output power increases with drive current. Laser has a higher efficiency and higher radiant flux than a LED. Therefore, laser will be used for long distance optical fibre communication. For short distance, LED will be used because sufficient low output power from it will be enough to overcome the attenuation of a short path. But the LED normally will have a longer life time compared to the laser [21].

In the receiver, photodiodes is the core in detecting the optical signal transmitted through the fiber. When light falls on the photodiodes, photons with sufficient energy can raise an electron from the valence band to the conduction band so pairing of electron-hole. As a result, a current produced proportional to the light illuminating the detector. The current will be converted into voltage signal by electronic circuits. The whole process is done by an opto-electronic devices, which convert a optical signal into electronic form and then further processed. The application of optical fibre is widely used in internet and telephone communication. The benefits of using optical fibre than copper are lower attenuation in long distance, suitable for higher frequencies and higher data rate transmission.

2.9.4 Sky wave communication

Sky wave is EM waves transmitted at high frequency (3 to 30 MHz), they will be reflected or refracted by the ionosphere. Therefore, worldwide communications can be achieved. The ionosphere consists of several layers of ionized plasma trapped in earth's magnetic field. It can be divided as D, E and F layers. When the transmitted frequency is above the maximum usable frequency, then signals will pass through F layer without being refracted. If it is lower than the lowest usable frequency, then it suffers high attenuation and signal is lost. Also D and E layers present during day and vanish at night. So F layer is the only layer for sky wave propagation at night. Frequency below 300 kHz will bend or refract in D and E layers. High frequency in the range of 0.3 to 4 MHz of EM wave will be attenuated or absorbed and above 4MHz will be passed unaffected [22]. Ionospheric transmission has a relatively small attenuation so it can be used for long range point to point communications of telegraphy, telephony and broadcasting. But the bandwidth is very narrow for transmission. Also interference may occur when the sky wave refracted to another area with its own terrestrial communication operating at similar frequencies. Therefore, it is now replacing by satellites slowly. Sky wave propagation is shown in figure 2.15 [23].

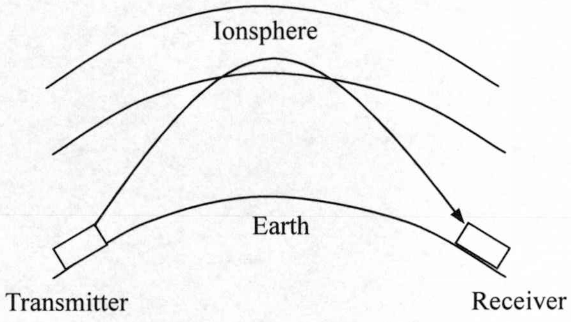


Figure 2.15 Sky wave propagation

2.9.5 Satellite communication

Satellite communication are used for long distance communication for long-distance telephone, wireless telephone, digitized television, digitized voice and internet access. It is also applied in navigation systems such as global positioning system (GPS). EM waves at frequency from tens of MHz to 40 GHz or higher are used for satellites communication. Higher frequencies allow greater bandwidth so more data can be transferred at a time. Lower frequencies have less free space loss and propagation losses such as rain, cloud and gaseous. The main loss is from the free space loss because the distance between the satellite and the ground station on the Earth is extremely long compared to any terrestrial communication. Other losses including atmospheric attenuation, ionospheric effect, rain effect and noise temperature. [22]

At high frequency, EM waves will go as a straight line and penetrate the atmosphere with some refraction by the atmosphere. The satellite is moving in its orbit and the velocity of the satellites is roughly about the same as the velocity of the rotation of

Earth. So the satellite is stationary with respect to the Earth. The communication link is set up by EM waves transmitted from the transmitter on Earth to the satellite in space, and then from the satellite back to the receiver on Earth [24]. A simple diagram of the satellite communication is shown in figure 2.16.

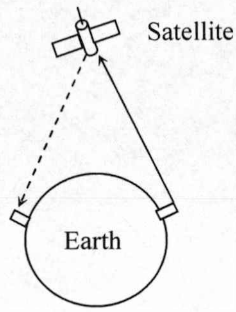


Figure 2.16 Satellite communication between two ground stations

Chapter 3

Electromagnetic theory

In this chapter, the background theories applied in this project are covered. It includes Faraday's law, Maxwell's equations, Debye equations and electromagnetic (EM) waves propagation in multiple dielectric medium. Water and seawater as a medium for propagation are the two main areas concerned in this project. Antennae used in transmitting and receiving the signals, theory of it have been discussed. To maximise the power delivered from the signal generator to the antenna or received at the receiver, transmission line theory is important and has been included in this chapter.

3.1 EM waves

EM waves produced from time – varying electric fields and magnetic fields. For the transverse electromagnetic plane wave, the electric field (E) is perpendicular to the magnetic field (H) and both are transverse to direction of the travel of the wave. The picture of EM wave travel in free space is shown in figure 3.1.

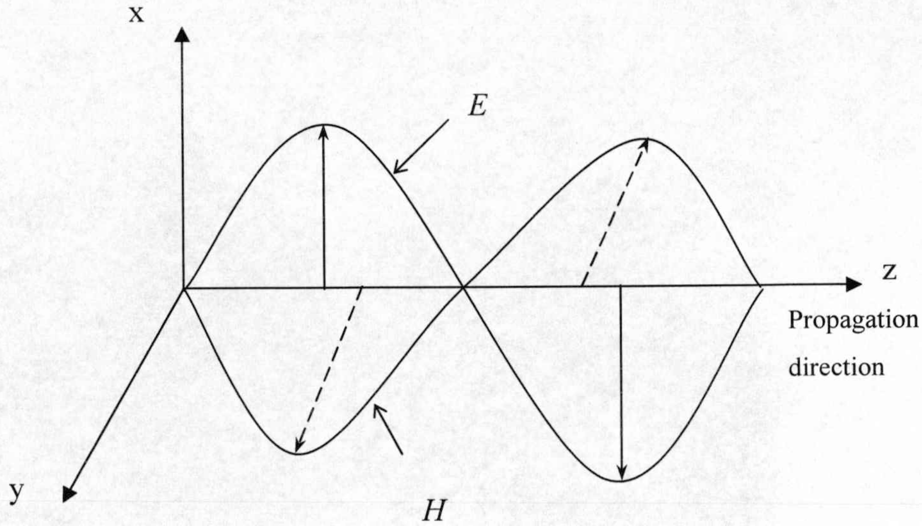


Figure 3.1 The transverse electromagnetic plane wave

For transverse electromagnetic plane wave, the ratio of:

$$\frac{E}{H} = Z_0 \tag{3.1}$$

where E (V/m) is the electric field, H (A/m) is the magnetic field and Z_0 is the characteristic impedance (ohms).

In free space, $\mu_r = 1$ with $\mu = \mu_0 \mu_r = 4\pi \times 10^{-7}$ H/m and $\varepsilon_r = 1$ with

$\varepsilon = \varepsilon_0 \varepsilon_r = 8.85 \times 10^{-12}$ F/m.

Here μ is the complex permeability, μ_0 is the permeability of free space and μ_r is the relative permeability of the media. Whilst ε is the complex permittivity, ε_0 is the permittivity of free space and ε_r is the relative permittivity of the media.

In free space, $Z_0 = \dfrac{E}{H} = \sqrt{\dfrac{\mu_0}{\varepsilon_0}} = 377$ ohms or $120\,\pi$ ohms.

In free space, the velocity of the EM wave is equal to 3×10^8 ms^{-1} which is equal to the speed of light, $c = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8$ ms^{-1}.

The wavelength (λ) of the EM wave can be calculated by the following equation:

$$\upsilon = f\lambda \tag{3.2}$$

where f is the frequency of the EM wave and υ is the velocity of the EM wave.

EM waves have a wide range of applications. The EM wave spectrum and applications are shown in table. 3.1.

Frequency (Hz)	**Wavelength (m)**	**Classification**	**Application**
3 – 30	10M – 100M	ELF	Detection of buried metal objects
30 – 300	1M – 10M	SLF	Communication with submerged submarine
300 – 3000	100k – 1M	ULF	Telephone audio range
3k – 30k	10k – 100k	VLF	Navigation, sonar
30k – 300k	1k – 10k	LF	Navigation, radio beacon
300k – 3000k	100 – 1000	MF	AM, maritime radio, direction finding
3M – 30M	10 – 100	HF	Facsimile, SW radio, citizen's band
30M – 300M	1 – 10	VHF	TV, FM, mobile radio, air traffic control
300M – 3000M	100m – 1	UHF	Radar, TV, navigation
3G – 30G	10m – 100m	SHF	Radar, satellite communication
30G – 300G	1m – 10m	EHF	Radar, space exploration
$10^{12} - 6 \times 10^{14}$	500n – 300μ	Infra-red	Night vision
8×10^{14} - 10^{19}	30p – 375n	Ultra-violet	Sterilization
10^{16} - 10^{21}	300^{-15} – 30n	X – ray	Medical diagnosis
Greater than 10^{19}	Less than 30 p	γ-ray	Food irradiation, cancer therapy

Table 3.1 The table of the spectrum of EM waves and its application [24]

3.2 Faraday's law

Michael Faraday experimentally demonstrated that a changing magnetic field produced an electric field by winding two separate coils on an iron toroid and placed a galvanometer in one circuit and a battery in the other. When the battery circuit is closed, the galvanometer deflects momentary. And the galvanometer deflects in the opposite direction when the battery circuit is open. A simple drawing of the experiment setup is shown in figure 3.2.

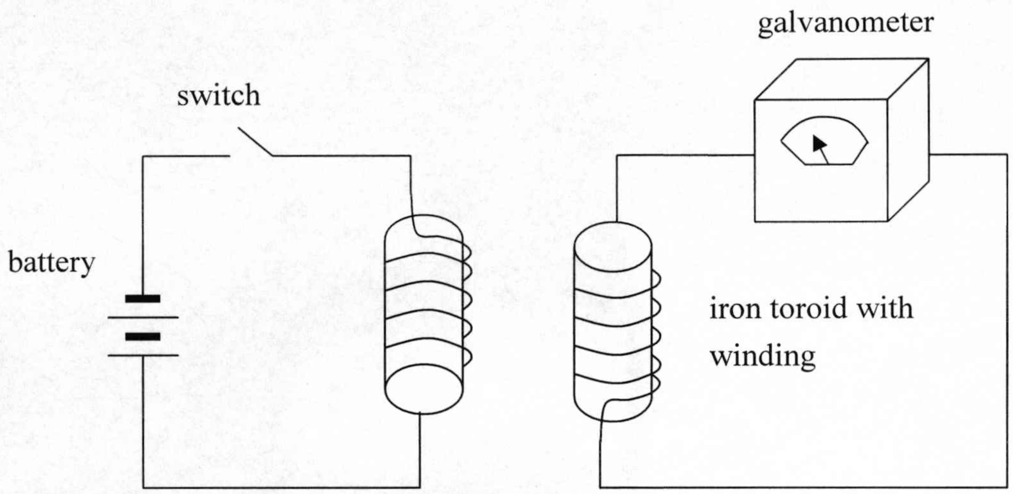


Figure 3.2 Faraday's experiment setup

Faraday's law [25]:

$$emf = -\frac{d\phi}{dt} \tag{3.3}$$

$$emf = \oint E \cdot dL = -\int_s \frac{\partial B}{\partial t} \cdot dS \tag{3.4}$$

$\frac{d\phi}{dt}$ is the time rate of change of the flux, whilst emf is the electromotive force produced and is measured in voltage. The minus sign means the induced voltage is in the direction opposing the change flux produced it. B is the magnetic flux density, A is the area of the loop and $\oint E \cdot dL$ is the line integral of E around the loop. $\int_s \frac{\partial B}{\partial t} \cdot dS$ is the surface integral of $\frac{\partial B}{\partial t}$ over loop area A. Therefore, the changing magnetic field produces a changing electric field which adds up around the loop to a changing voltage at the loop terminals. On closing the terminals, a time-varying current flows in the loop.

3.3 Maxwell's equations

Maxwell's equations are named because they are developed by James Clerk Maxwell. It consists of four equations which are based on the experimental work of Coulomb's law, Ampere's law, Faraday's law, and the principle of conservation of electric charge. Maxwell's equations are the four fundamental equations in electromagnetics.

Maxwell's equation in differential form listed as below [25]:

$$Curl\ E = \nabla \times E = -\frac{\partial B}{\partial t} \tag{3.5}$$

$$Curl\ H = \nabla \times H = J + \frac{\partial D}{\partial t} \tag{3.6}$$

$$Div\ D = \nabla \cdot D = \rho \tag{3.7}$$

$$Div\ B = \nabla \cdot B = 0 \tag{3.8}$$

Maxwell's equation in integral form listed as below [25]:

$$\oint E \cdot dL = -\int_s \frac{\partial B}{\partial t} \cdot dS \tag{3.9}$$

$$\oint H \cdot dL = I + \int_s \frac{\partial D}{\partial t} \cdot dS \tag{3.10}$$

$$\int_s D \cdot dS = \int_{vol} \rho\, dv \tag{3.11}$$

$$\int_s B \cdot dS = 0 \tag{3.12}$$

where E is the electric field intensity and measured in unit of V/m,

H is the magnetic field intensity and measured in unit of A/m,

D is electric flux density and measured in units of C/m^2,

B is the magnetic flux density and measured in units of T (tesla),

J is the electric current density and measured in units of A/m^2,

ρ is the volume charge density and measured in units of C/m^3,

S the area and measured in m^2.

Equation (3.5) is Faraday's law of induction after applying the Stokes' theorem to the closed line integral.

$$emf = \oint E \cdot dL = -\int_s \frac{\partial B}{\partial t} \cdot dS$$

$$\int_s (\nabla \times E) \cdot dS = -\int_s \frac{\partial B}{\partial t} \cdot dS$$

$$(\nabla \times E) \cdot dS = -\frac{\partial B}{\partial t} \cdot dS$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

It means that the electric field E arises due to a time changing magnetic flux density. And E is conservative.

Equation (3.6) is Ampere's law with a term added to include a time varying displacement current density ($\frac{\partial D}{\partial t}$). The physical interpretation of it is the magnetic field H can arise due to conduction current density J or displacement current density.

Equation (3.7) is the Gauss for electric fields. It means that the divergence of the electric flux density at a point is equal to the charge density at that point.

Equation (3.8) is the Gauss for magnetic fields. It implies that there are no sources or sinks of B. Therefore, B forms closed loops.

3.4 EM waves propagation in different dielectric medium

Both electric and magnetic flux densities (D, B) are interacting with E and H. They are known as constitutive relations. In materials that are homogeneous, the equations of D and B are shown in equations (3.13) and (3.14).

$$D = \varepsilon E \tag{3.13}$$

$$B = \mu H \tag{3.14}$$

where ε is the complex permittivity and μ is the complex permeability and $\mu = \mu_0 \mu_r$ and $\varepsilon = \varepsilon_0 \varepsilon_r$.

And ε_r is the relative permittivity of the media, μ_r is the relative permeability of the media. The values for free space are $\mu_r = 1$ and $\varepsilon_r = 1$.

Therefore, the values of electric and magnetic flux densities will be changed in different media.

The electric current density J in conductive media has the equation (3.15)

$$J = \sigma E \tag{3.15}$$

where σ is the conductivity of the media.

3.4.1 Plane EM waves propagation in free space

When the EM wave in free space, the medium is sourceless ($J = 0$) and $\varepsilon_r = \mu_r = 1$. The Maxwell's equations may be simplified to:

$$\nabla \times E = -\frac{\partial B}{\partial t} \tag{3.16}$$

$$\nabla \times H = \frac{\partial D}{\partial t} \tag{3.17}$$

$$\nabla \cdot D = 0 \tag{3.18}$$

$$\nabla \cdot B = 0 \tag{3.19}$$

In free space, the electric and magnetic flux densities are given by:

$$D = \varepsilon_0 E \tag{3.20}$$

$$B = \mu_0 H \tag{3.21}$$

The propagation velocity of the EM wave in free space which is equal to the speed of light is:

$$v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \text{ x } 10^8 \text{ ms}^{-1} = c \text{ (speed of light in free space)} \tag{3.22}$$

The intrinsic impedance of free space is,

$$Z_0 = \frac{E}{H} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377 \text{ ohms or } 120\,\pi \text{ ohms.} \tag{3.23}$$

3.4.2 Plane EM waves propagation in dielectrics

The medium for the EM waves propagation is assumed to be homogeneous (having constant μ and ε with position) and isotropic (μ and ε are invariant with field orientation). The homogeneous vector Helmholtz's equation is shown in equation (3.24) [26].

$$\nabla^2 E_s = -k^2 E_s \tag{3.24}$$

where k is the wave number and can be a complex number

$$k = \omega\sqrt{\mu\varepsilon} = k_0\sqrt{\mu_r \varepsilon_r} \tag{3.25}$$

And k_0 is the wave number in free space and is defined as:

$$k_0 = \frac{\omega}{c} \tag{3.26}$$

From the equation (3.24), the electric field in x direction, E_x:

$$\frac{d^2 E_{xs}}{dz^2} = -k^2 E_{xs} \tag{3.27}$$

The propagation constant, γ is:

$$\gamma = jk = \alpha + j\beta \tag{3.28}$$

where α is called the attenuation constant and is measured in units of Nepers/m, β is the phase constant and is measured in units of rad/m and ω is the angular frequency and is measured in units of radians.

A solution of (3.27) is [26]:

$$E_{xs} = E_{x0}e^{-jkz} = E_{x0}e^{-\alpha z}e^{-j\beta z} \tag{3.29}$$

Multiplying (3.29) by $e^{j\omega t}$ and taking the real part yields:

$$E_x = E_{x0}e^{-\alpha z}\cos(\omega t - \beta z) \tag{3.30}$$

From the equation (3.29), the plane wave propagates in the forward z direction with phase shift $e^{-j\beta z}$ but the amplitude of it decreases with increasing z due to the attenuation factor $e^{-\alpha z}$.

When plane EM waves passing through a material at high frequencies, the bound electrons or ion oscillations and dipole relaxation are alternately polarized by the applied electric field. Therefore, work is done against the molecular forces and result in energy losses [27]. The polarization varies with the applied electric field at the rate at low frequencies but when the frequency increases, the molecular forces between particles resist to follow the changing of electric field. So the polarization cannot keep in phase with the electric field. This effect is modelled by the complex permittivity of the material:

$$\varepsilon = \varepsilon' - j\varepsilon'' = \varepsilon_0(\varepsilon_r' - j\varepsilon_r'') \tag{3.31}$$

where ε' is the real part and ε'' is the imaginary part of the permittivity.

Putting (3.31) into (3.25), gives:

$$k = \omega\sqrt{\mu(\varepsilon' - j\varepsilon'')} = \omega\sqrt{\mu\varepsilon}\sqrt{1 - j\frac{\varepsilon''}{\varepsilon'}} \tag{3.32}$$

Taking the real and imaginary parts of jk from (3.32) [26],

$$\alpha = \mathrm{Re}\{jk\} = \omega\sqrt{\frac{\mu\varepsilon'}{2}}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)^{\frac{1}{2}} \tag{3.33}$$

$$\beta = \mathrm{Im}\{jk\} = \omega\sqrt{\frac{\mu\varepsilon'}{2}}\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2} + 1\right)^{\frac{1}{2}} \tag{3.34}$$

The phase velocity for a traveling wave is:

$$v_p = \frac{\omega}{\beta} \tag{3.35}$$

And the wavelength is:

$$\lambda = \frac{2\pi}{\beta} \tag{3.36}$$

The intrinsic impedance of this medium is:

$$Z_i = \sqrt{\frac{\mu}{\varepsilon' - j\varepsilon''}} = \sqrt{\frac{\mu}{\varepsilon'}} \frac{1}{\sqrt{1 - j(\varepsilon''/\varepsilon')}} \tag{3.37}$$

If we assume it is a lossless medium, or perfect dielectric then $\varepsilon'' = 0$, thus $\varepsilon = \varepsilon'$. From equation (3.33) and equation (3.34):

$$\alpha = 0 \quad \text{(lossless medium)} \tag{3.38}$$

$$\beta = \omega\sqrt{\mu\varepsilon} \quad \text{(lossless medium)} \tag{3.39}$$

The velocity in lossless medium is:

$$v_p = \frac{\omega}{\beta} = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \quad \text{(lossless medium)} \tag{3.40}$$

The intrinsic impedance in lossless medium is:

$$Z_{lossless} = \sqrt{\frac{\mu}{\varepsilon}} \tag{3.41}$$

In the case of conductive material, currents are formed by the motion of free electrons or holes under the influence of an electric field. When the conductivity of the material is finite, power is lost due to heating. The complex permittivity is related to the conductivity as:

$$\varepsilon'' = \frac{\sigma}{\omega} \tag{3.42}$$

To determine the state of a material whether it is conductive or dielectric, the loss tangent ($\varepsilon''/\varepsilon'$) is used as an indication and defined as [26]:

$$\tan\theta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon'} \tag{3.43}$$

If $\sigma = 0$, the medium is perfect dielectric or lossless. If $1 >> \varepsilon''/\varepsilon'$, then the medium is a good dielectric. If $1 << \varepsilon''/\varepsilon'$, then it behaves like a conductor. The propagation of a plane EM wave in good conductors will be discussed later. Substituting $\varepsilon'' = \sigma/\omega$ into equation (3.31), then the α and β for low loss dielectric ($1 >> \varepsilon''/\varepsilon'$) are [26]:

$$\alpha = \mathrm{Re}\{jk\} = j\omega\sqrt{\mu\varepsilon'}\left(-j\frac{\sigma}{2\omega\varepsilon'}\right) = \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon'}} \tag{3.44}$$

$$\beta = \mathrm{Im}\{jk\} = \omega\sqrt{\mu\varepsilon'}\left[1 + \frac{1}{8}\left(\frac{\sigma}{\omega\varepsilon'}\right)^2\right] \tag{3.45}$$

The intrinsic impedance of a good dielectric is:

$$Z_{G.dielectric} = \sqrt{\frac{\mu}{\varepsilon}}\left(1 + j\frac{\sigma}{2\omega\varepsilon'}\right) \tag{3.46}$$

3.4.3 Plane EM waves propagation in good conductors

When the loss tangent, $\varepsilon''/\varepsilon' >> 1$, EM wave propagating in this material can be considered as a good conductor. A high conductivity and large conduction currents are the properties of a good conductor. The attenuation constant (α) and the phase constant (β) can be derived from the equation (3.28) and (3.32), they are:

$$\alpha = \beta = \sqrt{\pi f \mu \sigma} \tag{3.47}$$

The skin depth (δ) is an important term when EM wave propagation is in a good conductor and is defined as [26]:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\alpha} = \frac{1}{\beta} \tag{3.48}$$

The electric field propagates along the conductor can be represented by the equation in (3.29). Substituting equation (3.48) into (3.29), this become:

$$E_{xs} = E_{x0} e^{-z/\delta} e^{-j(z/\delta)} \tag{3.49}$$

When $z = 0$, the amplitude of the electric field is at the surface of the conducting medium and is equal to $E_{xs} = E_{x0}$. When $z = \delta$, the amplitude of the electric field is:

$$|E_{xs}| = E_{x0} e^{-1} = E_{x0} \frac{1}{e} \tag{3.50}$$

The amplitude of the electric field is reduced to 0.368 of its original value when the waves propagate for every skin depth (δ).

From equation (3.48),

$$\beta = \frac{1}{\delta} \tag{3.51}$$

And equation (3.36),

$$\lambda = \frac{2\pi}{\beta} \tag{3.52}$$

Then the wavelength in a good conductor is:

$$\lambda = 2\pi\delta \tag{3.53}$$

Substitute equation (3.48) in to (3.35), the velocity of propagation along the good conductor is:

$$v_{conductor} = \omega\delta \tag{3.54}$$

For example, EM waves propagation in copper at 100Hz and 1GHz are used. And the conductivity of copper is $5.8 \times 10^7 \, S/m$.

The skin depth at 100Hz is:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{0.066}{\sqrt{f}} = 6.6 \times 10^{-3} m$$

The velocity at 100Hz is:

$$v_{conductor} = \omega\delta = 2\pi f\delta = 4.15m/s$$

The skin depth at 1GHz is:

$$\delta = \frac{1}{\sqrt{\pi f\mu\sigma}} = \frac{0.066}{\sqrt{f}} = 2.1\times10^{-6}m$$

The velocity at 1GHz is:

$$v_{conductor} = \omega\delta = 2\pi f\delta = 13.11\times10^{3}m/s$$

When the frequency increases, the skin depth is reduced. When the EM waves propagate the distance about 5 times skin depth (δ), the amplitude of the electric field is only 0.0067 of the original value. Therefore, at high frequency, EM waves can propagate at the surface of the conductor without penetrating inside the conductor because the skin depth is so short (e.g. at 1GHz skin depth, $\delta = 2.1\times10^{-6}m$).

Consider EM waves at the range of 1MHz to 20MHz propagate in seawater, the conductivity of seawater is 4Sm^{-1} and the relative permittivity is 81.

The loss tangent at 1MHz is:

$$\tan\theta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon'} = \frac{4}{(2\pi\times10^{6})(81)(8.85\times10^{-12})} = 888.1$$

The loss tangent at 20MHz is

$$\tan\theta = \frac{\varepsilon''}{\varepsilon'} = \frac{\sigma}{\omega\varepsilon'} = \frac{4}{(2\pi\times20\times10^{6})(81)(8.85\times10^{-12})} = 44.4$$

Since 888>>1 and 44.4>>1, then seawater is a good conductor when EM waves are propagating at the range of 1MHz to 20MHz.

The skin depth at 1MHz in seawater is:

$$\delta = \frac{1}{\sqrt{\pi f\mu\sigma}} = \frac{1}{\sqrt{\pi f(4\pi\times10^{-7})(4)}} = \frac{251.6}{\sqrt{f}} = 0.25m$$

And the wavelength at 1MHz is:

$$\lambda = 2\pi\delta = 1.57m$$

The velocity at 1MHz is:

$$v_{seawater} = \omega\delta = 1.57\times10^{6}ms^{-1}$$

The skin depth at 20MHz in seawater is:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{251.6}{\sqrt{f}} = 0.06m$$

And the wavelength at 20MHz is:

$$\lambda = 2\pi\delta = 0.38m$$

The velocity at 20MHz is:

$$v_{seawater} = \omega\delta = 7.54\times10^{6}ms^{-1}$$

The calculation of the skin depth of EM waves between 1MHz to 20MHz to propagate in seawater is too small, so it is impractical for communication in seawater to use EM waves at high frequency. This project used EM waves at the frequency range from 1MHz to 20MHz to propagate in seawater by creating a far field radiation. The existence of far field makes EM waves at that frequency range are possible to propagate and can be used in underwater communication. The near field follows the Maxwell's equation while the far field is due to the dipole oscillation of the water molecules created by the presence of an EM field in the skin depth region of the antenna [28].

3.5 Poynting's vector

The power carried by the EM waves is given by:

$$S = E \, x \, H \tag{3.55}$$

S is the Poynting vector measured in Wm^{-2}. It is an instantaneous power per unit area carried by the wave. The vector S shows the direction of the instantaneous power flow at a point. For a lossless medium, the propagation of the EM waves are in positive z direction and the electric and magnetic field are given by [26]:

$$E_x = E_{x0} \cos(\omega t - \beta z) \tag{3.56}$$

$$H_y = \frac{E_{x0}}{Z_i} \cos(\omega t - \beta z) \tag{3.57}$$

The Poynting's vector is [26]:

$$S_z = \frac{E_{x0}^2}{Z_i} \cos^2(\omega t - \beta z) \tag{3.58}$$

For a lossy dielectric, there is a phase difference between the electric field and magnetic field so they are given by:

$$E_x = E_{x0} e^{-\alpha z} \cos(\omega t - \beta z) \tag{3.59}$$

$$Z_i = |Z_i| \angle \theta \tag{3.60}$$

$$H_y = \frac{E_{x0}}{|Z_i|} e^{-\alpha z} \cos(\omega t - \beta z - \theta) \tag{3.61}$$

$\angle \theta$ is the phase angle between E_x and H_y

Then the Poynting vector is [26]:

$$S_z = \frac{E_{x0}^2}{|Z_i|} e^{-2\alpha z} \cos(\omega t - \beta z) \cos(\omega t - \beta z - \theta) \tag{3.62}$$

The average Poynting vector in phasor form can be obtain by integrating equation (3.62) and becomes:

$$S_{av} = \frac{1}{2}\frac{E_{x0}^2}{|Z_i|} e^{-2\alpha z} \cos\theta \qquad (3.63)$$

From equation (3.63), the average power density has a term $e^{-2\alpha z}$ which means it attenuates as $e^{-2\alpha z}$. While the electric and magnetic field attenuates as $e^{-\alpha z}$.

In vector form, the Poynting vector is:

$$S_{av} = \frac{1}{2}\mathrm{Re}\left(E_s \times H_s^*\right) \qquad (3.64)$$

H_s^* is the complex conjugate of H_s

3.6 Debye equations

The propagation of EM waves in fresh water can be explained by Debye equations. The basic principle is the polarization of dipoles moment in water with applied EM field. Water (H_2O) is a strong polar molecule formed with hydrogen and oxygen atoms with permanent dipole moment. When an electric field is applied to water, polarization occurs which is contributed by permanent dipole moment, then un-bonded polar molecules align with the electric field. Two simple diagrams of dipole molecules orientation before and after the applied electric field are shown in figure 3.3 and 3.4.

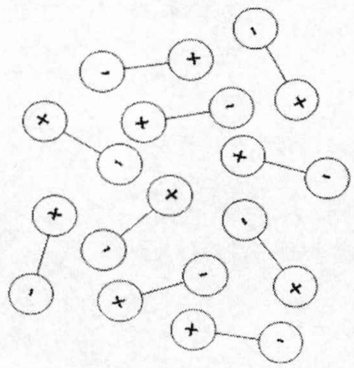


Figure 3.3 Dipole molecules orientation before the applied electric field

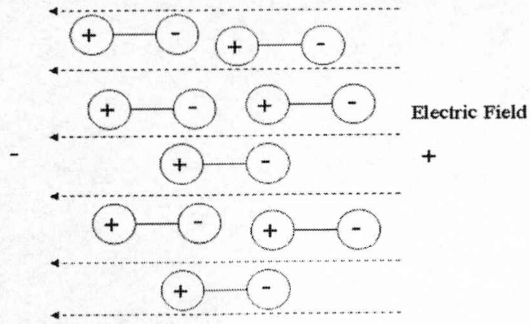


Figure 3.4 Dipole molecules orientation after the applied electric field

When the electric field is time varying, then the field direction will be reversed periodically. Therefore, the dipoles attempt to follow the changing of electric field but they are resisted by molecular force which is the hydrogen bond formed between the hydrogen and oxygen atoms. The molecular force likes a restoring force and tries to oppose the applied field so that the molecules can go back to the original position. At low frequency, there is enough time for the dipoles to line up with the field during each cycle so the polarization amplitude will be larger. But when the frequency increases, there is not enough time for dipoles to align with the field during each cycle and the amplitude of polarization is reduced. The time for the molecules to return to their equilibrium position after the removal of the applied electric field is called the relaxation time [29].

It is assumed that the ε_r is contributed by the polarization formed from permanent dipole moment (P_p) and is [29]:

$$D_p = \varepsilon_0 \varepsilon_r E = \varepsilon_0 E + P_p \tag{3.65}$$

The polarization formed from induced dipole moment (P_i) is:

$$D_i = \varepsilon_0 \varepsilon_\infty E = \varepsilon_0 E + P_i \tag{3.66}$$

The total polarization is:

$$D = \varepsilon_0 \varepsilon_s E = \varepsilon_0 E + P \tag{3.67}$$

The applied time varying electric field is $E = E_0 e^{-j\omega t}$. The rate of change of P_p is given by the instantaneous polarization from equilibrium divided by the relaxation time:

$$\begin{aligned} \frac{dP_p}{dt} &= \frac{P - (P_i + P_p)}{\tau} \\ \frac{dP_p}{dt} &= \frac{\varepsilon_0(\varepsilon_s - \varepsilon_\infty)}{\tau} E_0 e^{-j\omega t} - \frac{P_p}{\tau} \end{aligned} \tag{3.68}$$

Assuming that all polarization fields follow the driving field, the solution is:

$$P_p = \frac{\varepsilon_0(\varepsilon_s - \varepsilon_\infty)}{1 - j\omega\tau} E_0 e^{-j\omega t} \tag{3.69}$$

From equation (3.65), the relative dielectric permittivity is:

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 - j\omega\tau} \tag{3.70}$$

The real and imaginary parts of the Debye equations from equation (3.70) are given by [29]:

$$\mathrm{Re}\{\varepsilon_r\} = \varepsilon_r' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (\omega\tau)^2} \tag{3.71}$$

$$\mathrm{Im}\{\varepsilon_r\} = \varepsilon_r'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1 + (\omega\tau)^2} \tag{3.72}$$

where ε_s is the low frequency permittivity, ε_∞ is the high frequency permittivity, τ is the relaxation time and $\omega = 2\pi f$ the angular frequency.

The far field of EM waves propagating in seawater is due to the dipole oscillation of the water molecules which have a low attenuation [28]. The electric field attenuated at rate with distance z and is given by:

$$E = E_0 e^{-\alpha z} \tag{3.73}$$

From the equation (3.33), and simplified to:

$$\alpha = \frac{1}{2}\omega\sqrt{\mu\varepsilon'}\left(\frac{\varepsilon''}{\varepsilon'}\right) \tag{3.74}$$

From the Debye equation (3.71) and (3.72), with $\tau = 8.2\times10^{-12}$ s, $\varepsilon_s = 80$ and $\varepsilon_\infty = 3$

$$\varepsilon_r' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+(\omega\tau)^2}$$
$$\varepsilon_r'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1+(\omega\tau)^2}$$

For $\omega\tau << 1$,

$$\varepsilon_r' = \varepsilon_s = 80$$

$$\varepsilon_r'' = 77\omega\tau = 3.97\times10^{-3} f \quad (f \text{ in MHz})$$

Then $\varepsilon''/\varepsilon'$ is:

$$\frac{\varepsilon''}{\varepsilon'} = 49.6\times10^{-6} f \quad (f \text{ in MHz})$$

The attenuation coefficient from equation (3.74) becomes:

$$\alpha = \frac{1}{2}\omega\sqrt{\mu\varepsilon'}\left(\frac{\varepsilon''}{\varepsilon'}\right) = 4.65\times10^{-6} f^2$$

Therefore, the electric field attenuation is:

$$\frac{E}{E_0} = \exp\left(-4.65\times10^{-6} f^2 z\right) \quad (f \text{ in MHz}) \tag{3.75}$$

Let assume the distance z is 100m and the frequency for transmission is 10MHz, then the electric field at z is:

$$E = 0.95E_0$$

So the signal is still 95% of the original signal after transmitted for 100m. But in the real marine environment, attenuation will be higher due to the contribution of diffraction and reflection losses along the transmitting path.

3.7 Diffraction losses

Assume the radiation from the transmitter is a point source. The radiation spread from the source with omni-direction and extend outwards like a sphere. A simple figure is shown in figure 3.5. At distance z the power received at the receiver antenna with an area (A) is:

$$\frac{P_r}{P_t} = \frac{A}{4\pi z^2} \tag{3.76}$$

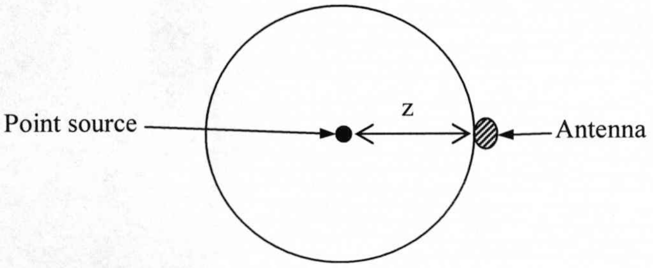


Figure 3.5 The radiation from a point sources transmitter

In the far field, the term $\sqrt{A}/2z\sqrt{\pi}$ will be multiplied to the equation (3.75) and become:

$$\frac{E}{E_0} = \exp\left(-4.65\times10^{-6} f^2 z\right)\times\frac{\sqrt{A}}{2z\sqrt{\pi}} \quad (f \text{ in MHz}) \tag{3.77}$$

3.8 Antenna

An antenna is a device that is used for transmitting and receiving EM waves. Mobility and wireless are the key factors for choosing the antenna in a communication system. The applications of antenna are everywhere today. Radio and television broadcasting are using a single transmitter station to emit the signal to unlimited number of receivers. Beside communication, antennae can also be applied in remote sensors to detect the scattered energy from some objects. Some properties and theories of the antenna will be discussed in here.

3.8.1 Radiation pattern

An antenna has its radiation pattern or polar diagram which shows the properties of it. A plot of the field strength radiated by the antenna in different angular directions is the radiation pattern. The radiation patterns are three-dimensional quantities involving the variation of field as a function of the spherical coordinates θ and φ. The spherical coordinates are shown in figure 3.6.

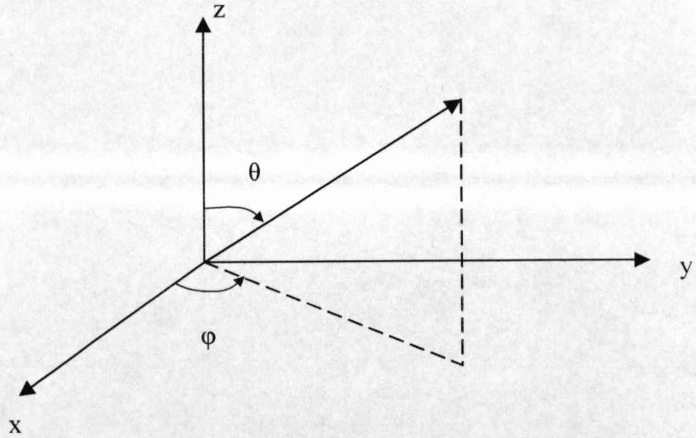


Figure 3.6 The spherical coordinates used

A typical radiation pattern in two dimensional is shown in figure 3.7. There are many beams or lobes. The maximum radiation direction among all the lobes is called the main lobes. Other lobes are called minor lobes. Back lobes are the minor lobes that are opposite the main lobe.

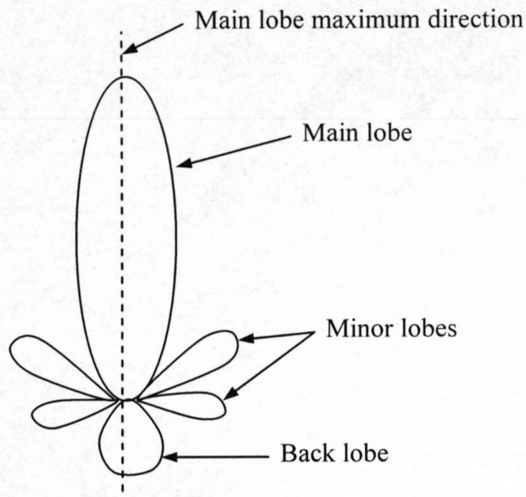


Figure 3.7 The spherical coordinates used

The width of the main beam can be defined as the half power beamwidth (HPBW) which is the angular separation between the maximum power of the beam and half of its value and is given by:

$$\frac{S(\theta,\varphi)}{S_{\max}} = 0.5 \tag{3.78}$$

$$\frac{E(\theta,\varphi)}{E_{\max}} = \frac{1}{\sqrt{2}} \tag{3.79}$$

where S is the Poynting vector, S_{max} is the maximum Poynthing vector, E is the electric field and E_{max} is the maximum electric field.

The diagram of half power beamwidth of a field pattern is shown in figure 3.8.

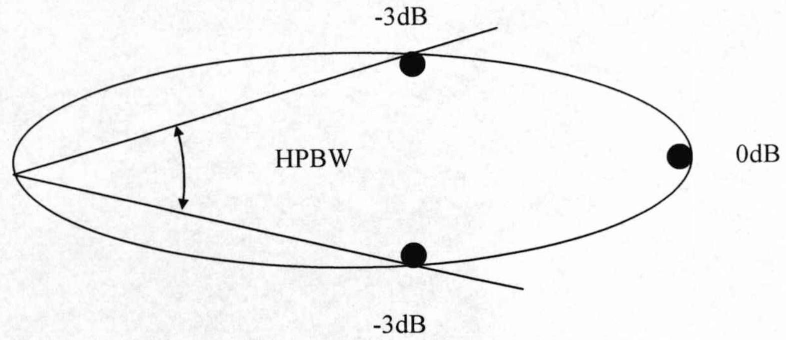


Figure 3.8 The diagram of half power beamwidth of a field pattern

3.8.2 Directivity and gain

The directivity and gain is very important parameters of an antenna

The radiation intensity defined as $\Phi(\theta,\varphi)$ and is measured in unit of W/sr [30].

$$\Phi(\theta,\varphi) = \frac{P_{rad}}{sr} \tag{3.80}$$

where P_{rad} is the power radiated by the antenna and sr is steradian.

$$1\ sr = \frac{solid\ angle\ of\ sphere}{4\pi} = \left(\frac{180}{\pi}\right)^2 (\deg)^2 \cong 3282.8 \text{ square degrees}$$

A reference is chosen for comparison to other antennae. Usually the isotropic source is chosen. The isotropic source is the antenna radiates a uniform distribution of electric field in all directions.

The reference radiation intensity is $\Phi_{ref}(\theta,\varphi)$, and the equation is (3.81)

$$\Phi_{ref}(\theta,\varphi) = \frac{P_{rad}}{4\pi} \tag{3.81}$$

The directivity of an antenna is defined as D [30],

$$D = \frac{\Phi_{\max}(\theta,\varphi)}{\Phi_{ref}(\theta,\varphi)} = \frac{4\pi}{\Omega_A} \tag{3.82}$$

where Ω_A is the half power beamwidth solid angle

The directivity in D(dB),

$$D\,(\text{dB}) = 10\log D \tag{3.83}$$

The gain of antenna is closely related to directivity and the relationships is

$$G = \xi D \tag{3.84}$$

where ζ is the radiation efficiency of the antenna. ($0<\zeta<1$)

3.8.3 Effective aperture

Considering an antenna for receiving a signal with a physical aperture A_p, then the power (P) received is [31]:

$$P = \frac{E^2}{Z}A_p = SA_p \tag{3.85}$$

The power radiated by the maximum effective aperture is assuming a uniform field at the aperture:

$$P = \frac{E_a^2}{Z}A_{em} \tag{3.86}$$

where A_{em} is the maximum effective aperture with no ohmic losses on the antenna.

The power radiated at a distance r in the far field assuming a uniform field E_r is:

$$P = \frac{E_r^2}{Z} r^2 \Omega_A \tag{3.87}$$

Solving equation (3.86) and (3.87) and substituting $E_r = E_a A_{em} / r\lambda$, the aperture-beam-area relation is:

$$\lambda^2 = A_{em} \Omega_A \tag{3.88}$$

Substituting equation (3.82) into equation (3.88), the directivity is:

$$D = \frac{4\pi A_{em}}{\lambda^2} \tag{3.89}$$

In practice, antennae are lossy so the effective aperture (A_e)is defined as:

$$A_e = \xi A_{em} \tag{3.90}$$

Multiplying radiation efficiency (ξ) on both sides in the equation (3.89) then the effective aperture is:

$$A_e = \frac{G\lambda^2}{4\pi} \tag{3.91}$$

3.8.4 Reciprocity

The transmitter antenna can be used as receiver antenna and vice versa due to the reciprocity theorem. For example, if e.m.f. is applied to the transmitter antenna, there is a current induced in the receiver antenna. When the same e.m.f. is applied to the receiver antenna, the same current will be induced in the transmitter antenna.

3.8.5 Friis transmission formula

Friis transmission formula is useful in determining the power received over a radio communication link. A simple diagram of a radio communication between a transmitter with an antenna having an effective aperture (A_{et}) and a receiver with an antenna having an effective aperture (A_{er}) is shown in figure 3.9.

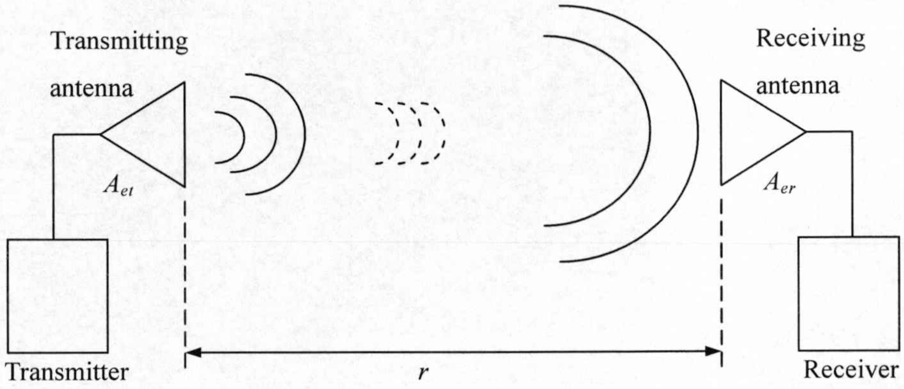


Figure 3.9 A communication between a transmitter and a receiver.

A lossless, matched antennae and the transmitting antenna with isotropic radiation are assumed. So all the power (P_t) from the transmitter is fed to the transmitting antenna. At distance (r), some of the power radiated from the transmitter picked up by a receiving antenna (P_r). The power collected at the receiver antenna will be the same as the power appears at the receiver. Therefore, the power per unit area at the receiving antenna (S_r) is [30]:

$$S_r = \frac{P_t}{4\pi r^2} \tag{3.92}$$

The transmitting antenna has a gain (G_t), so the power received at the receiving antenna will be increased and is given by:

$$S_r = \frac{P_t G_t}{4\pi r^2} \tag{3.93}$$

For the receiving antenna is lossless and matched, the power collected by its effective aperture (A_{er}) is:

$$P_r = A_{er} S_r = \frac{A_{er} P_t G_t}{4\pi r^2} \tag{3.94}$$

Also the gain of the transmitting antenna is:

$$G_t = \frac{4\pi A_{et}}{\lambda^2} \tag{3.95}$$

Substituting the equation (3.36) into (3.37), the Friis transmission formula is:

$$\frac{P_r}{P_t} = \frac{A_{er} A_{et}}{r^2 \lambda^2} \tag{3.96}$$

where P_r = received power, W

P_t = transmitted power, W

A_{et} = effective aperture of transmitting antenna, m^2

A_{er} = effective aperture of receiving antenna, m^2

r = distance between antennae, m

λ = wavelength, m

3.9 Types of antenna

Antenna is designed to suit its application and the radiation pattern is one of the most important factors in considering their applications. The radiation pattern of the antenna can be omni-directional (radiates equally in all directions) or directional (radiates more in one direction than the other directions). Basic antennae includes dipole, monopole and loop antenna and will be discussed in here.

3.9.1 Dipole

A very short electric dipole can be described when the physical length (L) is very short compared to the wavelength ($L << \lambda$). The diameter (d) of the dipole is also small when compared to its length ($d<<L$). A diagram of a very short electric dipole with the coordinates is shown in figure 3.9. Electric short dipole radiation properties are useful in applying any linear antenna. It is because many short dipoles connected in series can form a linear antenna and can be considered as a linear antenna.

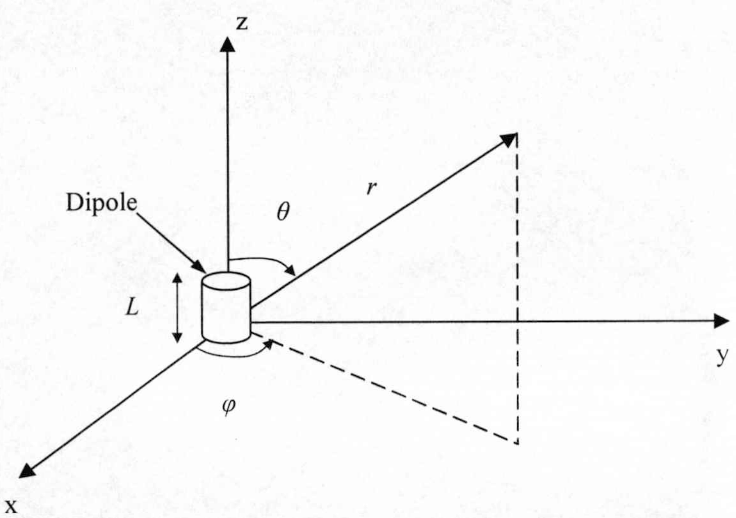


Figure 3.9 The diagram of very short dipole with their coordinates

The electric field generated by the dipole depends on the current distribution along the dipole. At the end of the wire, the current is zero whilst at the feeding point, the current is at a maximum. For an ideal dipole, the current distribution is uniform and is triangular shape for short dipole. A simple diagram of current distribution along the centre fed ideal and short dipole is shown in figure 3.10.

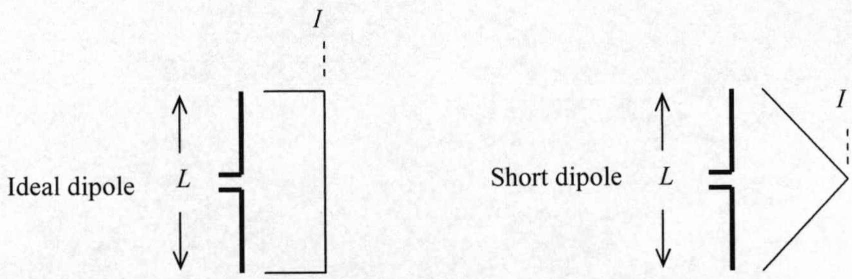


Figure 3.10 Current distribution of an the ideal and short dipole.

The radiation resistance of the ideal dipole (R_r) with uniform current is:

$$R_r = 80\pi^2 \left(\frac{L}{\lambda}\right)^2 \tag{3.97}$$

The radiation resistance of a short dipole with triangular current distribution is:

$$R_r = 20\pi^2 \left(\frac{L}{\lambda}\right)^2 \tag{3.98}$$

From equation (3.97), the radiation resistance increases with the frequency at fixed length. For an example, L=1m and the diameter of it is 0.1m. In free space at 10MHz, $\lambda = c/f = 30m$ and the radiation resistance with uniform current distribution is:

$$R_r = 80\pi^2 \left(\frac{1}{30}\right)^2 = 0.88\Omega$$

At 20MHz, the radiation resistance is:

$$R_r = 80\pi^2 \left(\frac{1}{15}\right)^2 = 3.51\Omega$$

The limitation of equation (3.97) is $L << \lambda$, so that the contributions of field of all phase difference from different parts of the dipole can be neglected. Errors will be introduced when the criteria of $L << \lambda$ cannot be met.

The radiation pattern in the far field of different length of dipole will be shown in figure 3.11, 3.12 and 3.13 which are simulated by the software EZNEC [32]. It is assumed that the antennae are symmetrically fed at the center, the diameter of it is small compared to the wavelength ($\lambda/100$) and the current distribution is sinusoidal in the antenna. It showed that the radiation pattern of the antenna is closely related to the wavelength and the physical length of the antenna.

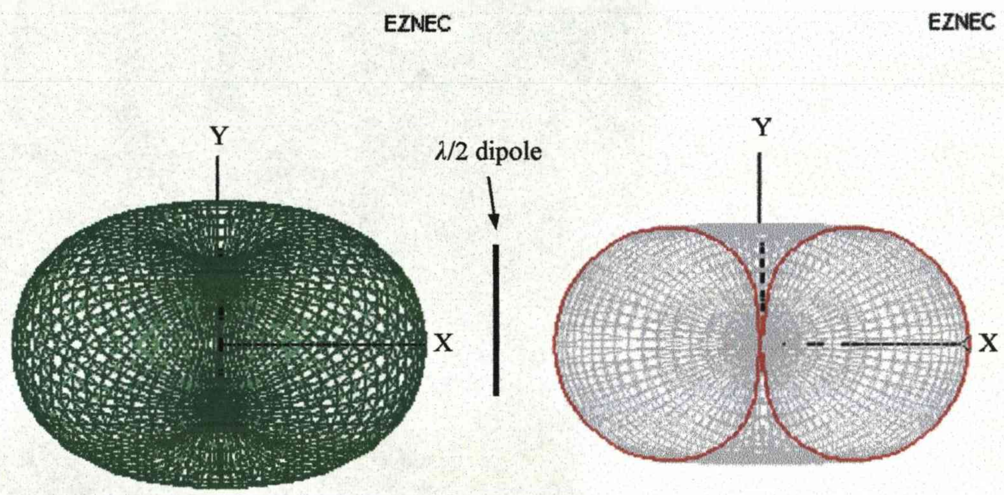


Figure 3.11 The radiation pattern of a $\lambda/2$ dipole in three-dimensional and two dimensional.

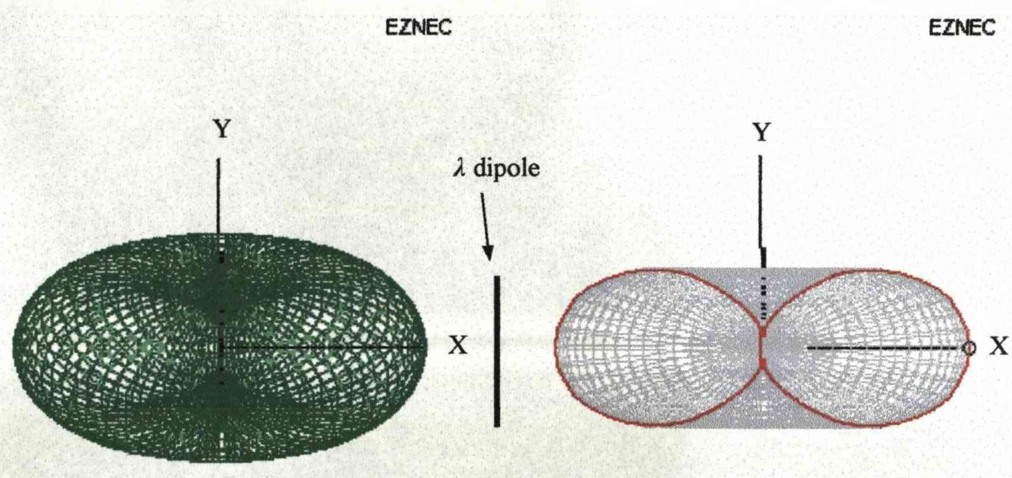


Figure 3.12 The radiation pattern of a λ dipole in three-dimensional and two dimensional.

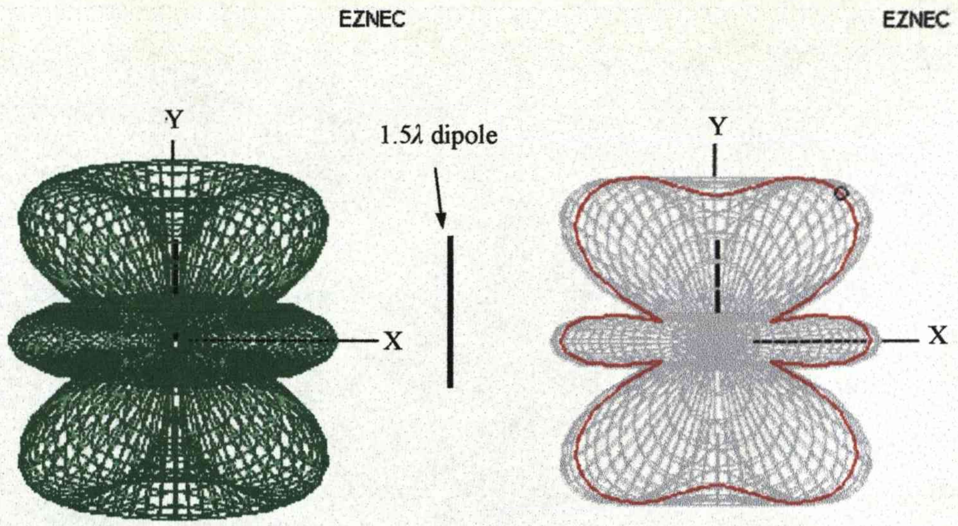


Figure 3.13 The radiation pattern a 1.5λ dipole in three-dimensional and two dimensional.

3.9.2 Monopole

A monopole antenna is driven against ground and with half of the size of a dipole. Assuming the ground plane is perfect and can be considered with infinity conductivity. The electric field is reflected by the ground plane and the diagram is shown in figure 3.14.

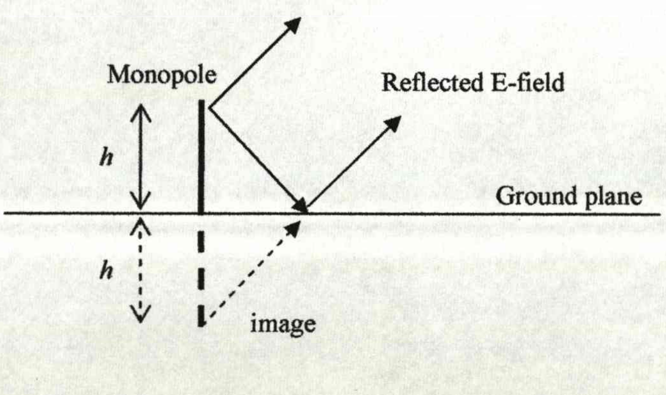


Figure 3.14 A monopole driven against ground plane

There is no power radiated below the ground plane so the electric field is over the top hemisphere. If the current fed to the dipole is the same as the monopole, then the power radiated by the monopole will be half of the dipole so:

$$P_{monopole} = \frac{1}{2} P_{dipole}$$

$$I^2 R_{r,monopole} = \frac{1}{2} I^2 R_{r,dipole}$$

$$R_{r,monopole} = \frac{1}{2} R_{r,dipole} \tag{3.99}$$

Substituting equation (3.98) in (3.99) and $L = 2h$,

$$R_{r,monopole} = 10\pi^2 \left(\frac{2h}{\lambda}\right)^2$$

The radiation resistance of the monopole is: □

$$R_{r,monopole} = 40\pi^2 \left(\frac{h}{\lambda}\right)^2 \tag{3.100}$$

The radiation pattern of the monopole is shown in figure 3.15.

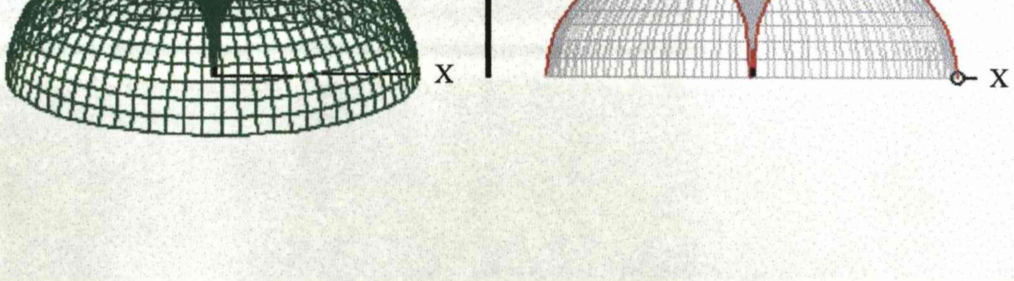


Figure 3.15 The radiation pattern a $\lambda/4$ dipole in three-dimensional and two dimensional [32].

3.9.3 Loop antenna

For a small circular loop antenna, the radiation pattern is depending on the area of the loop. So a small square loop antenna can be used for illustration instead of a small circular loop antenna as long as the physical size of the loop antenna is small compared to the wavelength. A diagram of a vertical square loop antenna with its coordinates is shown in figure 3.16.

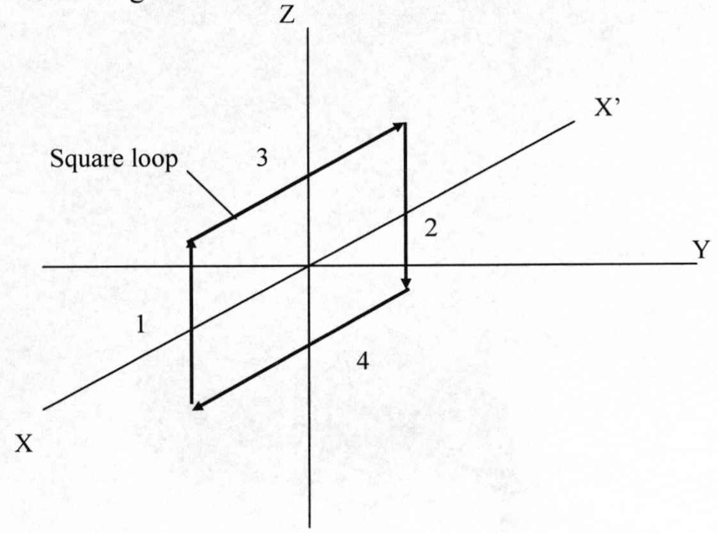


Figure 3.16 The loop antenna diagram [33]

The vertical square loop antenna has radiation from the four doublets, two from vertical and two from horizontal. The diagram is shown in figure 3.17. As the electric field due to doublets 3 and 4 cancelled to each other only the electric field due to doublets 1 and 2 to give a resultant electric radiation field.

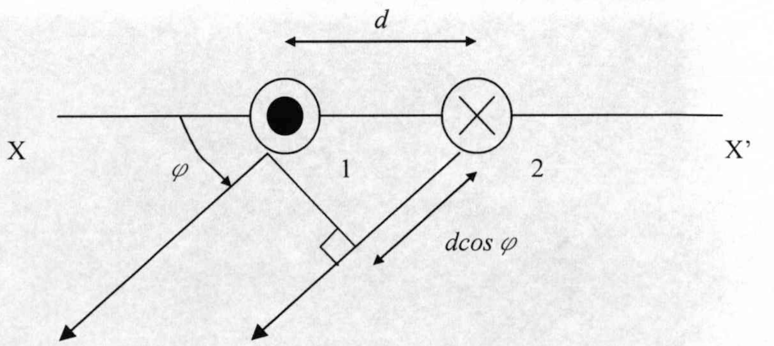


Figure 3.17 The diagram of resultant electric field from doublets 1 and 2 [33]

The power radiated from the loop antenna P is [30]:

$$P = 160\pi^4 I_0^2 \left(\frac{A}{\lambda^2}\right)^2 \tag{3.101}$$

And $P = 0.5\ I_0^2 R_r$

$$P = 160\pi^4 I_0^2 \left(\frac{A}{\lambda^2}\right)^2$$

where I_0 is the peak current, A is the area in the loop and R_r is the radiation resistance.

Therefore, the radiation resistance of a small loop antenna (R_r) is [30]:

$$R_r = 320\pi^4 \left(\frac{A}{\lambda^2}\right)^2 \tag{3.102}$$

$$\text{or} \quad R_r \approx 31200 \left(\frac{A}{\lambda^2}\right)^2$$

The radiation resistance of a small loop antenna with one or more turns is given by:

$$R_r \approx 31200 \left(\frac{nA}{\lambda^2}\right)^2 \tag{3.103}$$

where n = number of turns

The radiation pattern of a $\lambda/10$ square loop antenna is shown in figure 3.18.

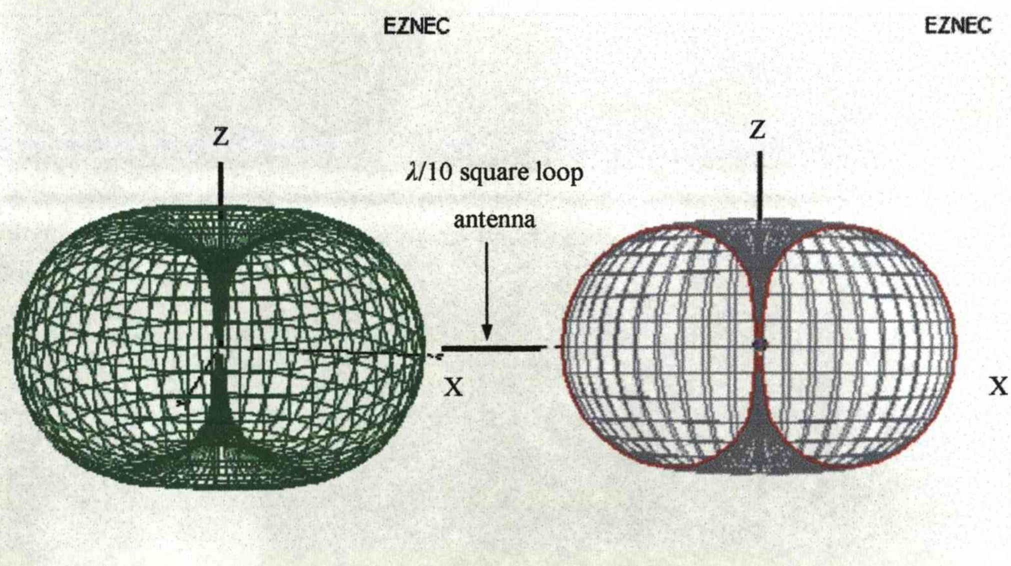


Figure 3.18 The radiation pattern a $\lambda/10$ square loop antenna in three and two dimensional [32].

For example, a double loop antenna with diameter 0.32m and at 10MHz the wavelength in free space is 30m. The radiation resistance of it is:

$$R_r \approx 31200\left(\frac{2\pi(0.16)}{30^2}\right)^2 \approx 1\times10^{-3}\Omega$$

At 20MHz, the radiation resistance is:

$$R_r \approx 31200\left(\frac{2\pi(0.16)}{15^2}\right)^2 \approx 15.9\times10^{-3}\Omega$$

A loop antenna can be considered as a small loop antenna when βa < 0.33 and considered as a large loop when $\beta a > 5$, where a is the radius of the loop and $\beta = \dfrac{2\pi}{\lambda}$.

For a single large loop antenna, the radiation resistance is [30]:

$$R_r \approx 3720\frac{a}{\lambda} \tag{3.104}$$

3.10 Radiation efficiency

The radiation efficiency can be defined as:

$$\xi = \frac{P_{rad}}{P_{Input}} = \frac{P_{rad}}{P_{rad} + P_{loss}} = \frac{I^2 R_r}{I^2(R_r + R_{loss})}$$

$$\xi = \frac{R_r}{R_r + R_{loss}} \tag{3.105}$$

where R_{loss} is the ohmic losses in heating up the antenna only. For a lossless antenna, $\xi = 1$ and less than 1 when the ohmic losses is presented. At radio frequencies, the R_{loss} is depending on the material of the antenna. It is assumed that the material used to make the antenna is a good conductor so the EM waves will be attenuated when propagating inside to the conductor. Due to the skin depth, EM waves can only propagate along the surface of the conductors and will not penetrate inside. This is called the skin effect and a simple diagram of skin effect is shown in figure 3.19. The shaded region is the propagation of EM waves while the white region inside the shaded region has no EM waves. Therefore, the area for current to pass through is reduced by the skin effect and the resistance is increased.

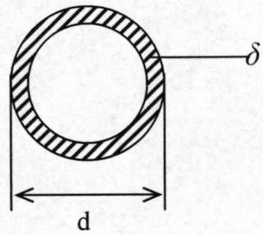


Figure 3.19 Diagram of the skin effect in a conductor at radio frequency

To calculate the resistance loss, it is assumed the diameter (*d*) of the conductor is much larger than the skin depth (δ). The resistance of the conductor is:

$$R_{loss} = \frac{l}{\sigma A} \tag{3.106}$$

The area *A* is:

$$A = 2\pi r \delta \tag{3.107}$$

Substituting equation (3.107) into (3.106) and $\delta = \dfrac{1}{\sqrt{\pi f \mu \sigma}}$

$$R_{loss} = \frac{l}{2r}\sqrt{\frac{\mu f}{\pi \sigma}} = \frac{l}{d}\sqrt{\frac{\mu f}{\pi \sigma}} \tag{3.108}$$

where r is the radius, *d* is the diameter and *L* is the length of the conductor, m

3.11 Transmission line

Transmitting electric energy and signals from one point to another can be achieved by using transmission line. Using alternation current to transmit the signal through a conductive line from the source to load, the length of the transmission line is important. When the distance for transmission is long, then a time delay will occur which causes a phase shift problem. The length of the transmission line (l) can be considered long when it is longer than the wavelength ($l>\lambda$). The basic elements of a lossless transmission line are capacitors and inductors whilst resistors form the line terminations. They can be considered as lumped elements or distributed elements depending on the length of the transmission in the order of wavelength. A good approximation can be made if the length of transmission line is less than a tenth of the wavelength of the signal, lumped elements would be assumed. To investigate the transmission line, it should be broken into many very short length so that ($\Delta z<<\lambda$). It is assumed that the EM wave is transmitting along the line in a "Transverse Electromagnetic (TE) mode". A diagram of a coaxial transmission line is shown in figure 3.20. When the transmission line is broken into short length (Δz), the circuit model of a transmission line in short length is shown in figure 3.21.

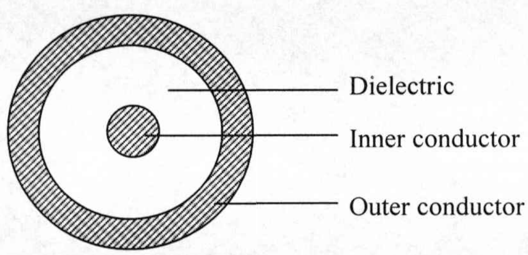


Figure 3.20 A diagram of a coaxial transmission line

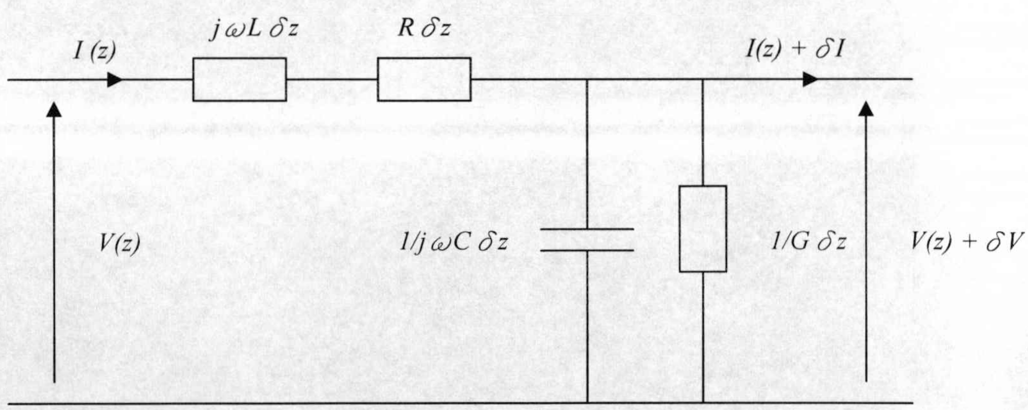


Figure 3.21 Circuit model of a transmission line in short length

where R is the resistance of both and inner and outer conductors per meter, G is the conductance per meter of the insulator, L is the inductance per meter, C is capacitance per meter and ω is the angular frequency.

The two important equations for transmission lines are as follows [26]:

$$V(z) = V^+ e^{-\gamma z} + V^- e^{+\gamma z} \tag{3.109}$$

$$I(z) = I^+ e^{-\gamma z} - I^- e^{+\gamma z} \tag{3.110}$$

where $V(z)$ is the voltage at z, V^+ is the magnitude of the incident wave phasor, V^- is the magnitude of the reflected wave phasor, $I(z)$ is the current at z, I^+ is the magnitude of the incident wave phasor, I^- is the magnitude of the reflected wave phasor, z is the short length of the transmission line and γ is the propagation constant.

From equation (3.109) and (3.110), it has forward and backward propagation waves and the propagation constant (γ) in the transmission line is equal to [26]:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \tag{3.111}$$

The characteristic impedance (Z_0) of the transmission line is equal to [26]:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{3.112}$$

The load reflection coefficient (Γ_L) is the ratio of the amplitude of reflected wave to the incident wave V^- / V^+ and is given by [26]:

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{3.113}$$

where Z_L is the impedance of the load and Z_0 is the characteristic impedance of the transmission line.

When $Z_L = Z_0$ then $\Gamma_L = 0$ and there is no reflected wave formed and the transmission line is said to be matched.

When $Z_L = 0$, then $\Gamma_L = -1$, the incident wave is reflected with a phase shift of 180 degrees but the amplitude of the reflected wave is equal to the incident wave.

A reflection coefficient at distance L from load (Γ) is equal to [34]:

$$\Gamma = \Gamma_L e^{-2\gamma L} \tag{3.114}$$

where L is the length of the transmission line from the load.

The input impedance (Z_{in}) is equal to:

$$Z_{in} = Z_0\left(\frac{1+\Gamma}{1-\Gamma}\right) \tag{3.115}$$

The transmission coefficient is defined as [34]:

$$\tau_c = \frac{V_L}{V_0} = 1+\Gamma = \frac{2Z_L}{Z_L + Z_0} \tag{3.116}$$

During the transmission, the incident power will be reflected from the load. The power lost due to reflection is given by [34]:

$$P_r = |\Gamma|^2 P_i \tag{3.117}$$

The power transmitted to the load is given by [34]:

$$P_t = \left(1-|\Gamma|^2\right)P_i \tag{3.118}$$

3.12 Impedance matching

The impedance of the source and the load should be matched in the transmission line to minimize reflections from the load before transmitting the signal.

Matching circuit is used to maximum the transmission of power from the source to the antenna. If the resistance of the source (signal generator) and the load (antenna) is not matched, the standing wave will be formed and reflected back to the sources in the transmission line.

Voltage standing wave ratio (*VSWR*) can be used to describe the how well the transmission line and the load is matched with the source.

$$VSWR = \frac{(1+|\Gamma_L|)}{(1-|\Gamma_L|)} = \frac{V_{\max}}{V_{\min}} \tag{3.119}$$

where Γ_L is the load reflection coefficient, V_{max} is the maximum voltage and V_{min} is the minimum voltage along the transmission line

For a perfect matched load and the transmission line, $|\Gamma_L| = 0$ and $VSWR = 1$. No standing waves are formed thus all power is being transmitted from the source to the load. When *VSWR* closer to 1, less reflections back to the source in the transmission line. The higher the *VSWR*, the more reflections to the source in the transmission line.

Theoretically, the whole system after introducing the matching circuit should have $VSWR = 1$ in the experiment. But practically, *VSWR* around 2 is acceptable.

The block diagram of the whole system with matching circuit is shown in figure 3.22.

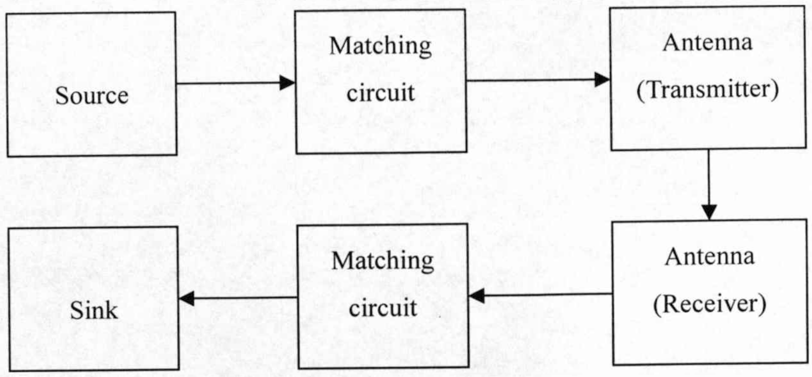


Figure 3.22 The block diagram of the matching circuit position in the system

3.12.1 RF transformer for impedance matching

An RF transformer can be used to match two circuits. It contains primary and secondary coils. It is similar to the normal transformer. The function of it is used to step-up in one side of the circuit and step-down in the other side or vice versa, so that the two impedances are matched. The diagram of a RF transformer is shown in figure 3.23.

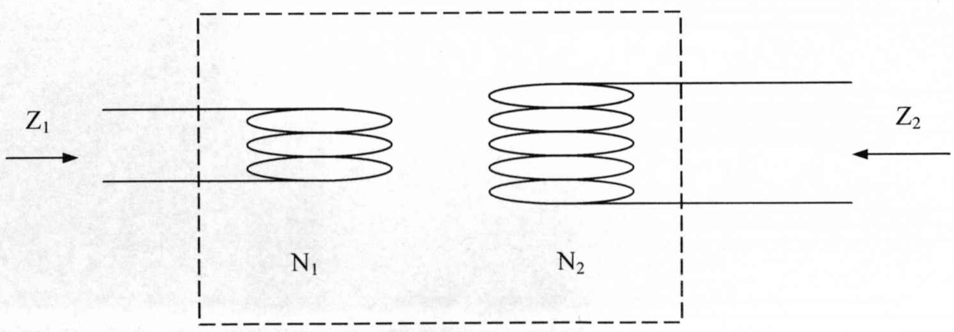


Figure 3.23 The diagram of a RF transformer

The equation to calculate the number of turns of the coil in the RF transformer to match the circuit in both sides is:

$$\frac{N_1}{N_2} = \left(\frac{Z_1}{Z_2}\right)^2 \tag{3.120}$$

where N_1 is the number of turns of coil in primary coil, N_2 is the number of turns of coil in secondary coil, Z_1 is the impedance at primary of the transformer and Z_2 is the impedance at the secondary of the transformer.

3.12.2 Matching circuit

Matching circuit consists the components of inductors, capacitors or both inductors and capacitors in the circuit. The components can be arranged in series or in parallel as long as they can be used to match the circuit. This method will be discussed later in detail in the Chapter 4 Methodology.

Chapter 4

Methodology

This chapter starts with introducing the design of antennas, transmitter and receiver and the way to construct them. This is followed by giving information about the electronics inside the transmitter box and explaining the function of each component and the associated basic theories. After that, describing the details of trials performed in both tank, Albert Dock and the Loch Linnhe together with the instruments and equipment used. Finally, information about the new design of the system is included.

4.1 Construction of the loop antennae

A hollow copper wire with diameter 6mm was prepared to desirable length. The antenna was bent into the required shape, namely a single loop antenna, or a double loop antenna. Connectors were constructed at both ends. After that, the whole copper wire was sheathed by heat shrink. Two types of connectors were used for connecting the antenna to the electronic drive systems. For trials in the laboratory tank, plastic connectors were used, but in the Albert Dock and the Loch Linnhe, Jupiter connectors made of metal alloy were used. This is because the Jupiter connector gave extra support strength and water- proof for the connection between the antenna and the transmitter in the seawater. As the water pressure in the Albert Dock and the Loch Linnhe is much higher than in the tank, then importantly the Jupiter connector prevents the leakage of seawater into the transmitter due to the high pressure environment.

Figure 4.1 and figure 4.2 show two types of antennas were made in experiment.

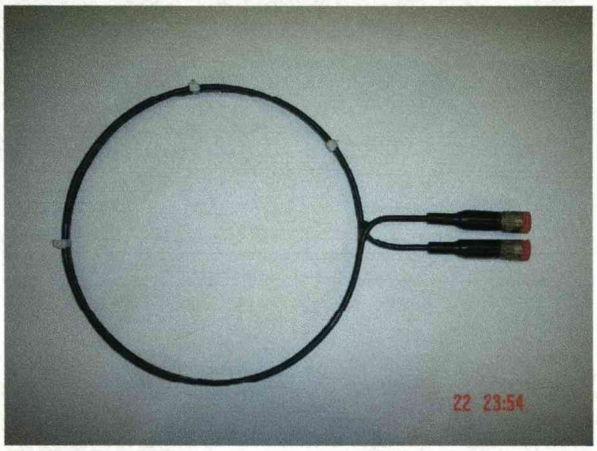


Figure 4.1 A 32cm double loop antenna with Jupiter connector

Figure 4.2 A 32 cm double loop antenna with plastic connector

The Jupiter connector is shown in figure 4.3

Figure 4.3 The Jupiter connector in an antenna

4.2 Transmitter and receiver used in the Albert Dock and the Loch Linnhe

Both transmitter and receiver electronics housing are made from stainless steel cylindrical tube. Stainless steel is chosen for the material of the transmitter because it provides physical strength to the transmitter and to withstand the water pressure in deep water to prevent leakage of water. Also it does not corrode or rust easily within the seawater. If not, the transmitter box will be rusted and weakened as time goes by. Another advantage is that the metal wall acts as a heat sink for the power amplifier. Heat is taking away from the power amplifier to the transmitter box then to the surrounding environment. The transmitter is powered by the battery inside it and therefore is operated without external electrical connections. Communication is set up through fibre optics between the transmitter and a laptop for remotely controlling such activities as switching on or off of the signal to save the battery power and monitoring the battery level, temperature and humidity inside the transmitter. The picture of the transmitter is shown in figure 4.4. The picture of the transmitter with the electronics inside it is shown in figure 4.5.

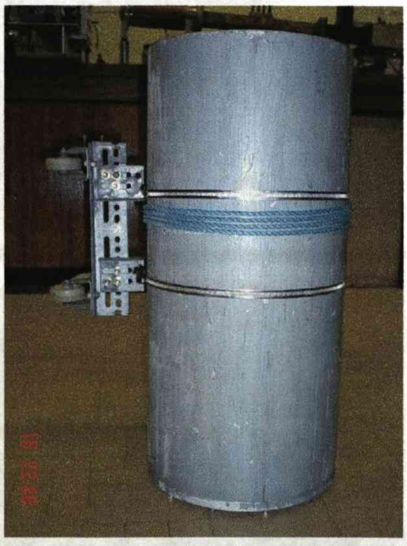


Figure 4.4 The transmitter metal box

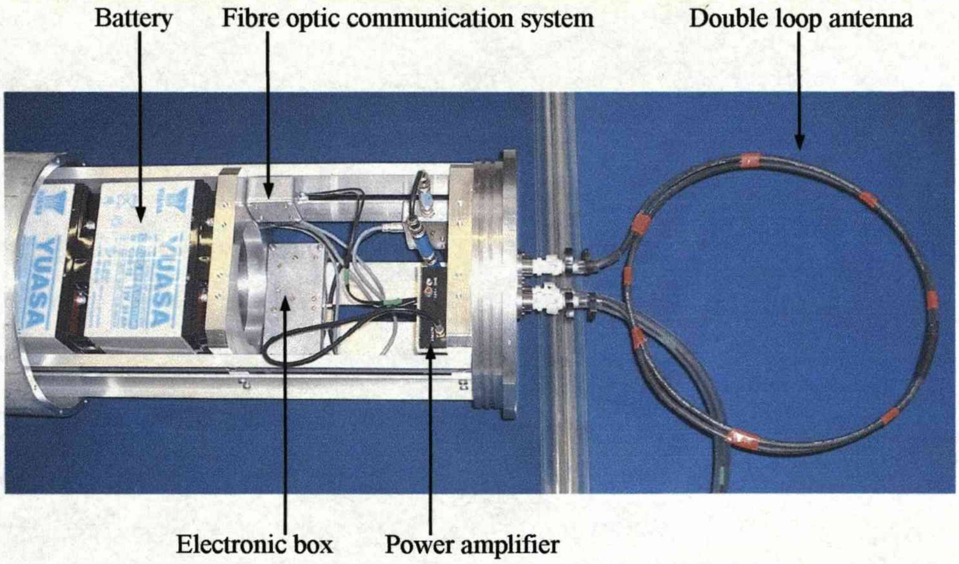


Figure 4.5 The transmitter box with electronics and battery

The receiver construction is much simpler, an antenna is attached to the box lid and to receive the signal and a matching circuit is inside the receiver to match the antenna to 50 ohms. Finally, it is connected to spectrum analyzer for recording the results. The picture of the receiver and the spectrum analyser are shown in figure 4.6 and 4.7.

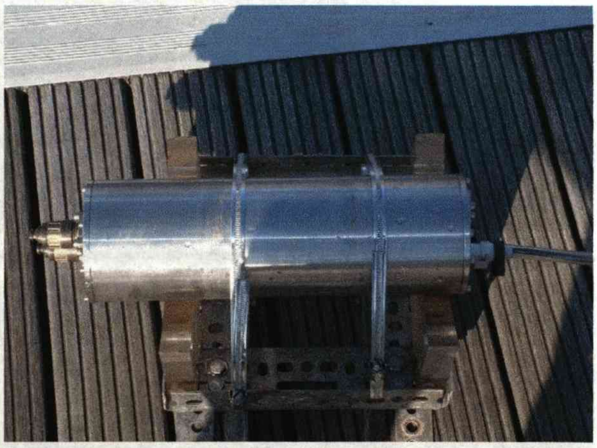


Figure 4.6 The metal receiver

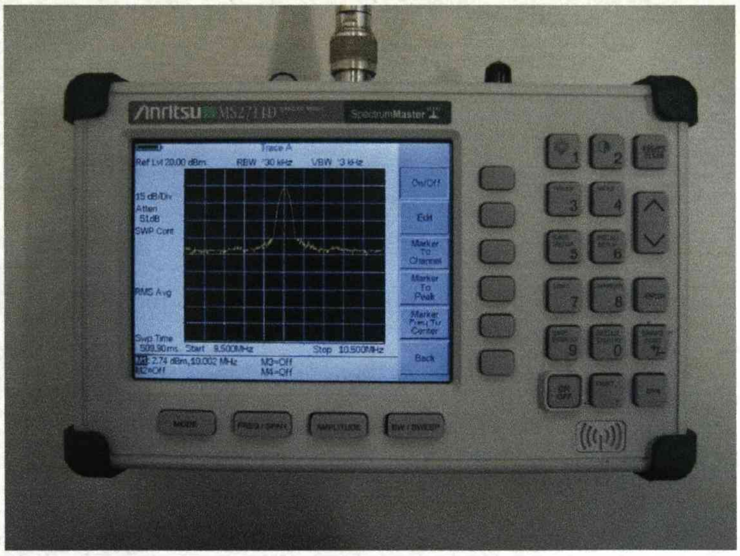


Figure 4.7 The spectrum analyzer Anritsu MS2711D

4.3 Transmitter and receiver used in the laboratory tank experiments

The transmitter and receiver systems used in the laboratory tank are identical. They are made of plastic because water pressure in tank is smaller than in a real marine environment and light in weight so easier for handling and performing experiments. The picture of it is shown in figure 4.8.

Figure 4.8 The transmitter in the laboratory tank

4.4 Electronic system

A block diagram of the electronic system is shown in figure 4.9 and the picture of the constructed electronic box is shown in figure 4.10. The function of each part of the electronics and components of the transmitter is explained individually. Microprocessor control unit is the central part of the whole system. It controls all the other electronic units and allocates processes in sequence. Processes include turning on or off the low noise amplifier and the Direct Digital Synthesizer (DDS), setting the gain of the variable gain amplifier and the frequency generated by the DDS according to the user setting, collecting the data from the humidity sensor, temperature sensor and battery monitoring circuit and sending information to the lap top. It was programmed so it can be communicated to an external lap top computer via fibre optics.

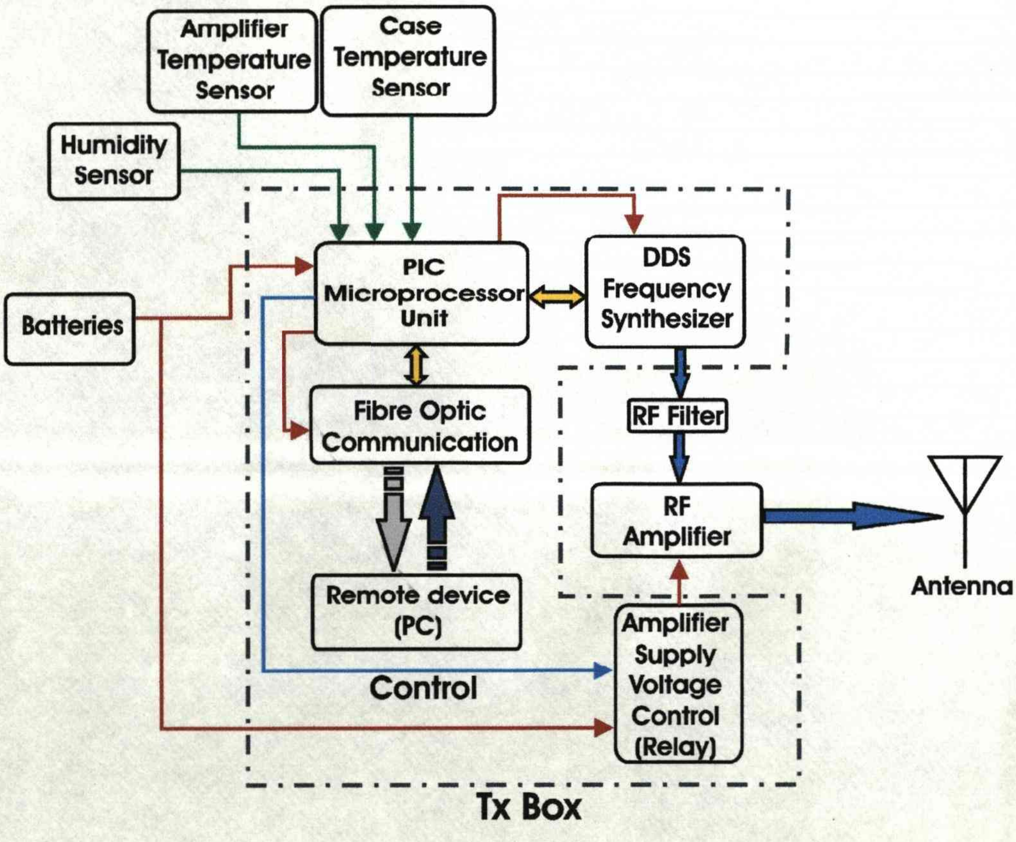


Figure 4.9 The block diagram of electronic system

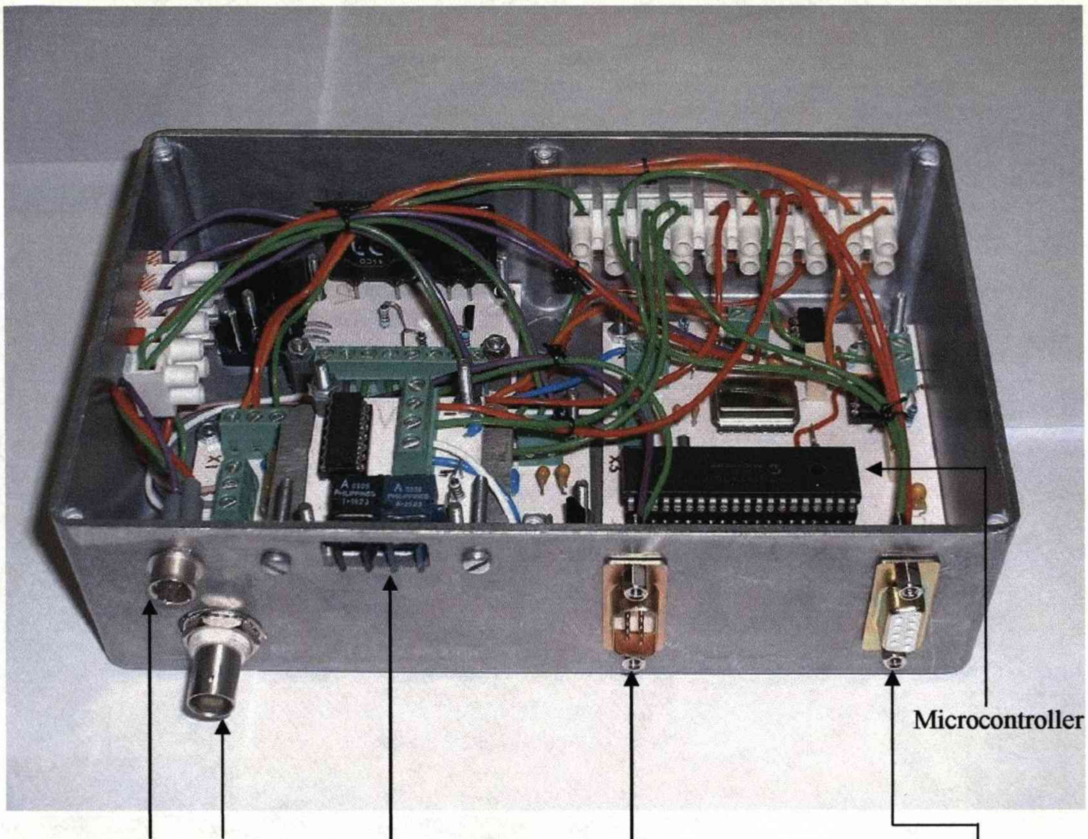


Figure 4.10 The picture of the constructed electronic box

4.5 Direct Digital Synthesizer (DDS)

Direct Digital Synthesis (DDS) is a radio frequency (RF) signals generator. It generates waveform directly by using a digital technique. The magnitude of sine wave is non-linear so it is difficult to generate. But the phase of it is linear, therefore, precise sine wave can be generated with a given reference interval.

A phase accumulator is used to assemble the phase component of the output signal. Continuous sine wave is periodic and repeated itself every period. The range of phase numbers are multiplied and become digital value in phase accumulator. Then the phase information is converted into a sinusoidal value using a sine function table. The sine function table stores a number relating to the voltage required for each value of phase on the sine wave. As the amplitude of the sine wave is directly mapped by the phase information. So referring to the sine function table stored in Read Only Memory (ROM), the phase information will be converted into amplitude. Finally, the digital value contains both phase and amplitude information is converted into analogue signal by using the Digital to Analogue Converter (DAC). The block diagram of the DDS is shown in figure 4.11.

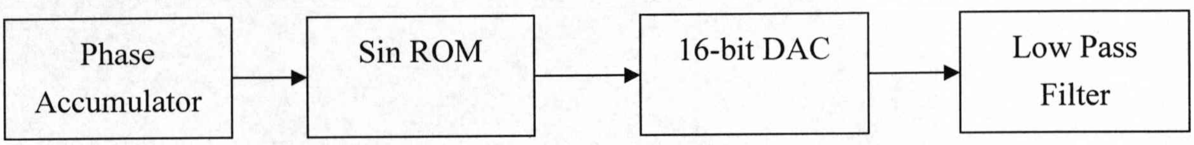


Figure 4.11 A block diagram of DDS

One of the major problems of DDS is an alias signal. The alias signal is spurious signal generated by DDS. Either side of the clock frequency and its multiples generate images of the signal. For example if desired frequency is 2MHz and the clock frequency is 20MHz. The alias signal will be at 18MHz and 22MHz, 38MHz and 42MHz and 58MHz and 62MHz … … etc. The problem can be solved by using a low pass filter or band pass filter depending on its application. It is because the signal strength (dBm) of the spurious signal is largely attenuated after passing through a low pass or band pass filter while the desired frequency stays the same. The shape of the sine wave may be slightly distorted depending on the bandwidth of the filter used.

Phase increment between different sample points correspond to the frequency generated. The higher frequency is the larger phase increment. As the phase reaches the full cycle value faster in the phase accumulator when a larger increment is used. So changing the phase increment can alter the frequency generated by DDS.

The signal to noise ratio (SNR) of DDS at the output of DAC is depending on the number of bits of DAC according to the follow equation [18]:

$$SNR = (6.02N + 1.76)\ dB \tag{4.1}$$

where N is the number of bits and SNR is in dB.

The higher value of SNR the better the signal is. From the above equation, SNR is proportional to N. Increasing the number of bits of DAC will increase the quality of the signal. If $N = 10$, $SNR = (6.02 \times 10 + 1.76)\ dB = 61.96\ dB$

The ease of generation of different frequencies of DDS can be achieved by setting the communication link between a laptop and the microprocessor via optical fibres by using user-friendly software. The microprocessor is programmed according to the DDS so generation of desired frequency can be achieved. This advantage is essential in underwater communication. Tuning of frequency can be done remotely at the top station without actually touching or opening the transmitter to replace the crystal oscillation to alternate the frequency for transmission. The DDS AD9832 from Analog Devices was used in the electronic box because it is a single unit with a digital to analog converter built in and requires only a few external components to complete the whole circuit. The required word for sending to DDS in hexadecimal form to vary the frequency from 1 to 10MHz is given in table 4.1.

Frequency (MHz)	Word (hexadecimal)
1	CCCCCCD
2	1999999A
3	26666667
4	33333334
5	40000000

(a)

Frequency (MHz)	Word (hexadecimal)
6	4CCCCCCD
7	5999999A
8	66666666
9	73333333
10	80000000

(b)

Table 4.1 The word for setting frequency in DDS

4.6 Low Noise Amplifier (LNA) circuit

The sine wave from the output of DDS is amplified by a Low Noise Amplifier (LNA). Since the propagation of sine wave along the circuit is alternating current, the transmission line approach is taken into account. For maximum transfer of power from the output of DDS to the input of LNA, the impedance of LNA (Z_{LNA}) is equal to the conjugate of the impedance of the DDS at output (Z_{DDS}).

$$Z_{LNA} = Z^{*}_{DDS} \tag{4.2}$$

If it is mismatched, reflection of waves will be formed in the circuit and hence, the transfer of power will be decreased. When designing a LNA circuit in radio frequency application, matching is very important. Some other factors also need to be considered, for example, the stability, third order intercept performance, bandwidth and the power consumption.

Designing a LNA circuit with unconditional stability is the aim. Any load presented at the input or output of the circuit will not make the circuit oscillate or unstable is the definition of unconditional stability. The main causes of instability are internal feedback of transistor, external feedback around the transistor caused by external circuit and too much gain outside the operation of the range of frequencies.

The LNA should have a good linearity within the range of frequencies interested. The third order intercept performance is a good figure to show how linear the LNA is.

The bandwidth should be narrow enough to reject other frequencies not interested. So the gain of frequencies within the bandwidth will be higher than those outside the bandwidth. Thus, the signal to noise (SNR) ratio will be increased.

The low power consumption of LNA circuit is appreciated. It is because the reduction of the amount of power consumption means that the transmitter can work for a longer time without the replacement of battery inside the transmitter. Therefore, the replacement of battery is not frequent.

The noise figure of LNA is typically lower than the normal amplifier (NB<2.5dB), which is good for increasing the sensitivity of the communication system. The disadvantage of LNA is the gain of it will be lower than normally other amplifier. The gain of LNA circuit is usually less than 15dB.

Sometimes it is not possible to attain all the requirements in LNA circuit. So trade-off of the properties is needed to suit for individual needs.

The LNA MAN-1LN from Mini-Circuits was used. A picture of the circuit assembles with a DDS and a LNA on Printed Circuit Board (PCB) is shown in figure 4.12.

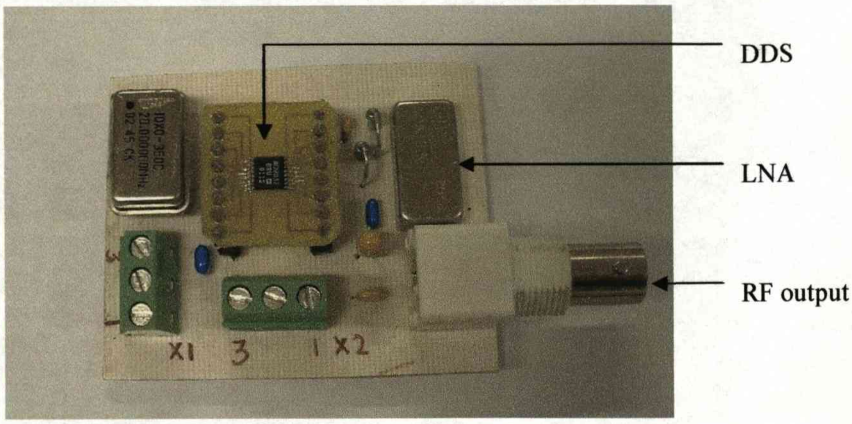
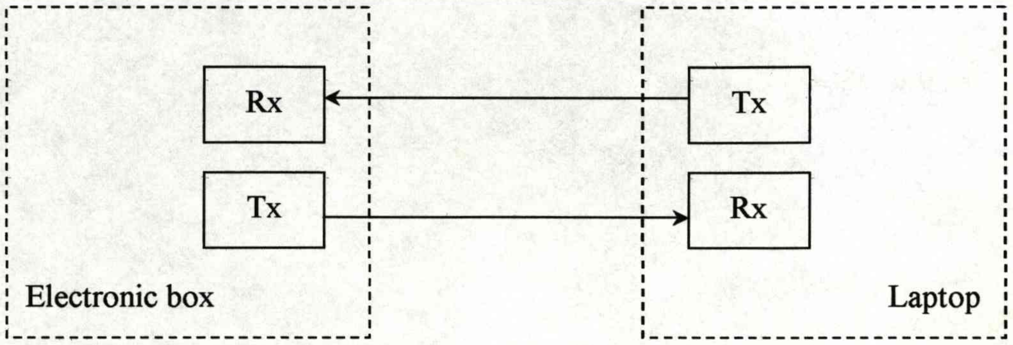


Figure 4.12 The picture of DDS and LNA constructed on PCB

4.7 Fibre optics communication system

Fibre optics is the link between the microprocessor inside the transmitter and the laptop outside the transmitter. Coaxial cables or other electrical wires are not interlinked between transmitter and laptop. This is because the electrical wires are vulnerable to the electromagnetic waves emitted from the antenna. The data transferred by the electrical wire will have a high rate of errors.

To avoid the interference between the electromagnetic waves and the data link, fibre optics is used instead of the normal electrical wire. As fibre optics does not suffer from electromagnetic waves interference at all. Therefore, the data stream sending to and receiving from transmitter will not be altered by the EM waves to introduce errors. When constructing the fibre optics link, two-fibre optics assemble together to set up a link between the laptop and the transmitter. One is for transmission of data and the other is for reception. This is how the communication link set up between the transmitter and laptop above the sea. The optical transmitter and receiver used were HFBR-1523 and HFBR-2523A from Agilent Technologies. A block diagram of fibre optics system and a picture of the circuit are shown in figure 4.13 and figure 4.14



Tx is Transmitter and Rx is Receiver

Figure 4.13 The block diagram of the fibre optics system

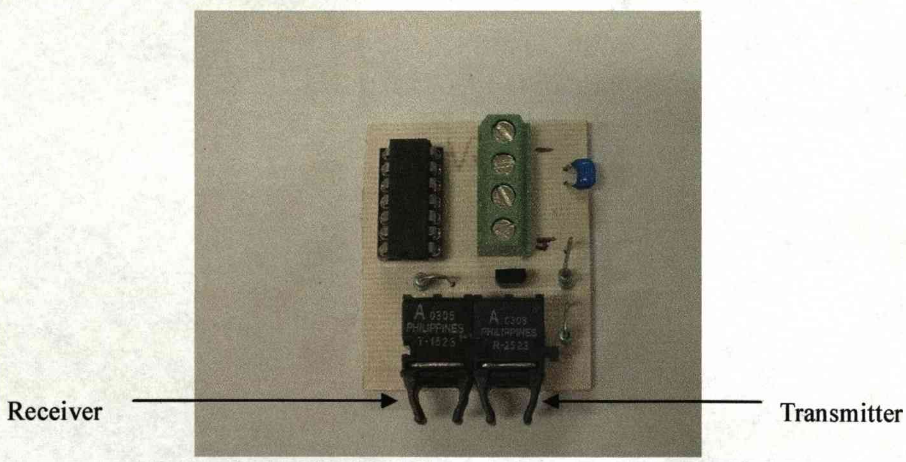


Figure 4.14 The picture of the circuit of fibre optics

4.8 The monitoring system

A monitoring system was introduced in the transmitter to keep track of the temperature, humidity and battery level of it. The purpose of it was to give more information inside the transmitter and to check the condition of it.

4.8.1 Humidity and temperature sensor

A humidity sensor HIH-3610 from Honeywell is installed inside the electronic box. The purpose of it is to detect the leakage of seawater into transmitter. If there is a leakage, people will know immediately and take the transmitter out of water. A temperature sensor LM35DZ from National Semiconductor with a temperature range from 2 to 150 degree Celsius is to monitor the temperature inside the transmitter. It is used to prevent the overheating of the components in the transmitter. Most likely, the power amplifier before the signal is fed to the antenna is the major contribution of heat. It must be cooled down by heat sink to maintain its linearity and performance. If not, the power amplifier will stop functioning properly.

4.8.2 Battery monitoring circuit

The voltage of the power supply of the transmitter is monitored by a voltage follower circuit and scaled down within the range of detection of the microcontroller. Then the voltage is recorded by the microcontroller. Data from the microcontroller is extracted to the laptop via optical fibre by a program. Finally, the battery level is presented on the laptop through the program. Information relating to the battery level is very important. As the battery level drops below a threshold level, the power amplifier does not have enough voltage to perform amplification. Thus, the gain of it will be decreased or totally turned off. The indication of battery level can also give the idea of how long the transmitter can work for, when the battery should be replaced and the whole system is working in normal condition.

4.9 Power amplifier

Both input and output of the power amplifier should be matched to minimize the loss of power during transmission before launching in an antenna. If it is badly matched with the antenna, too much power will be reflected back to the amplifier from the antenna. This may damage the power amplifier or may cause it to stop functioning properly. Matching is a must for radio frequency circuit to maximize the efficiency of the whole system.

Normally, the gain of the power amplifier will be at least 20dB. But this also means that it drains a lot of current. Therefore, the lifetime of the transmitter is reduced. Introducing a switch is very useful in reducing the power consumption. A switch is implemented in the electronic circuit to extend the lasting time of the transmitter in the seawater. It is because when the power amplifier is not in use, it is turned off to save the battery.

The ultra broadband 30Watt power amplifier BBM1C3KFL with passband (1 to 500 MHz) from the Empower RF System was used in the Albert Dock and the Loch Linnhe. The gain of the amplifier's output can be varied between 25dB to 30dB by controlling the variable gain circuit from 0 to 5V direct current (DC). For an amplifier having a good linearity, the gain is proportional to the voltage at variable gain circuit. In reality, saturation occurs at certain voltage level. This means when the voltage is increased beyond this voltage level, the gain will not be increased due to saturation. The gain curve will be flattened after that voltage level. The graph is shown in figure 4.15.

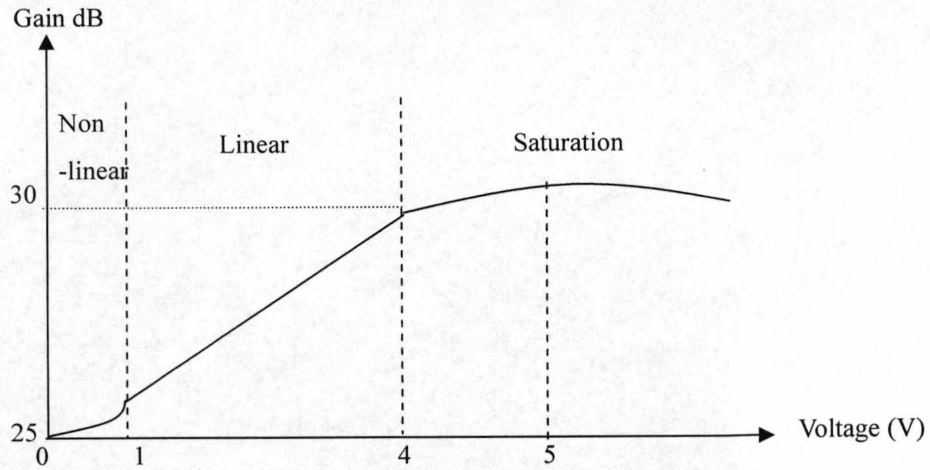


Figure 4.15 The gain curve of a variable gain amplifier

When setting the gain of the amplifier, it is better to be operated within the linear region because the gain can be predicted.

4.10 Antenna characteristics

The resistance of the antenna varied with the frequency for transmission, thus it is important to measure the resistance of it at the operating frequency. Then matching can be introduced to optimise the power transfer at designed frequency.

4.10.1 Measuring the impedance of antennae

The antenna was assembled to the receiver. Then the receiver was put into the seawater. The impedance of the antenna was recorded by a network analyzer (hp 8753E) which is a vector network analyzer. It can be used to measure both amplitude and phase properties of the signal. Swept frequency measurement determines the impedance of the antenna across a given range of frequencies. For example, if we choose 1MHz is the starting frequency and 20MHz is the stopping frequency. A set of impedances of the antenna within 1M to 20MHz is calculated. Therefore, a wide range of the operating frequencies can be chosen to be matched and operated for transmission. Various display function is supported by network analyzer. Among those display, the Smith Chart and VSWR graph are useful in interpreting the results in matching. The Smith Chart is good for determining the impedance while VSWR is checking the efficiency of power transmission before matching and after matching. In the experiment, an impedance scan and Smith Chart of a 32cm double loop antenna in seawater was plotted. Results of them are useful in constructing the matching circuit between the antenna and the signal generator. A Smith Chart is shown in figure 4.16.

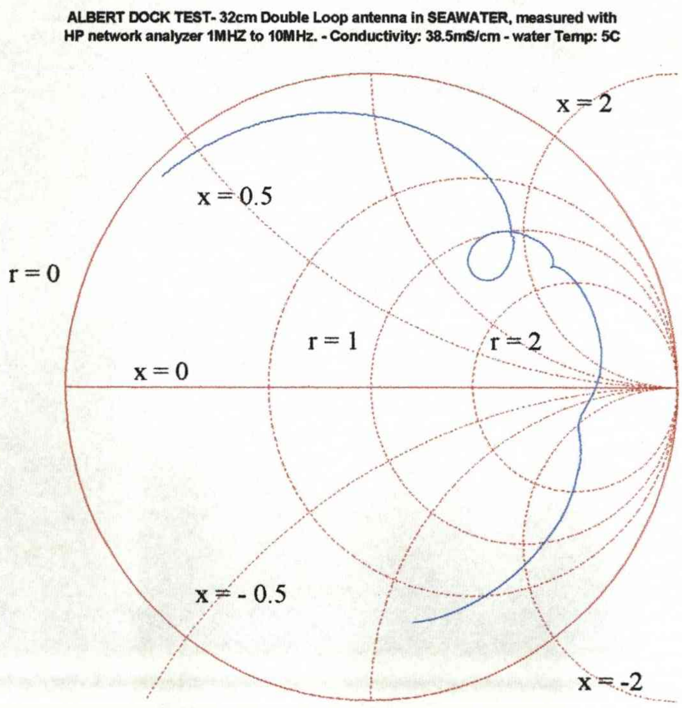


Figure 4.16 The Smith Chart of a 32cm double loop antenna in seawater

4.10.2 Matching circuit

The impedance of the antenna needed to match the signal generator (RF output) which is 50 ohms. When the antenna was matched to 50 ohms then the source and the load (antenna) had the same impedance. Therefore, no standing wave is formed. To match the antenna, the impedance value of the antenna in seawater at the transmitting frequency must be known.

Results of the impedance scan of the antenna in seawater were measured by the network analyzer and used in the LC match software [35]. Then the required matching circuit and the values of capacitors or inductors were calculated. The picture of the LC match software is shown in figure 4.17.

Sometimes more than one matching circuits were shown in the program, all of them are calculated to match the system to VSWR equal to 1 so any one of circuits was chosen and made for convenience. The matching circuit may be any combination of Series capacitor, Series inductor, Shunt capacitor or Shunt inductor. Three of the combination diagrams of the matching circuit are shown in figure 4.18, 4.19 and 4.20.

The VSWR of the system within the range of $1 < VSWR < 3$ is reasonable after matched. If the VSWR is higher than 3 (more than 24.9% power are reflected), then the matching circuit may need to be rebuilt or using other matching methods.

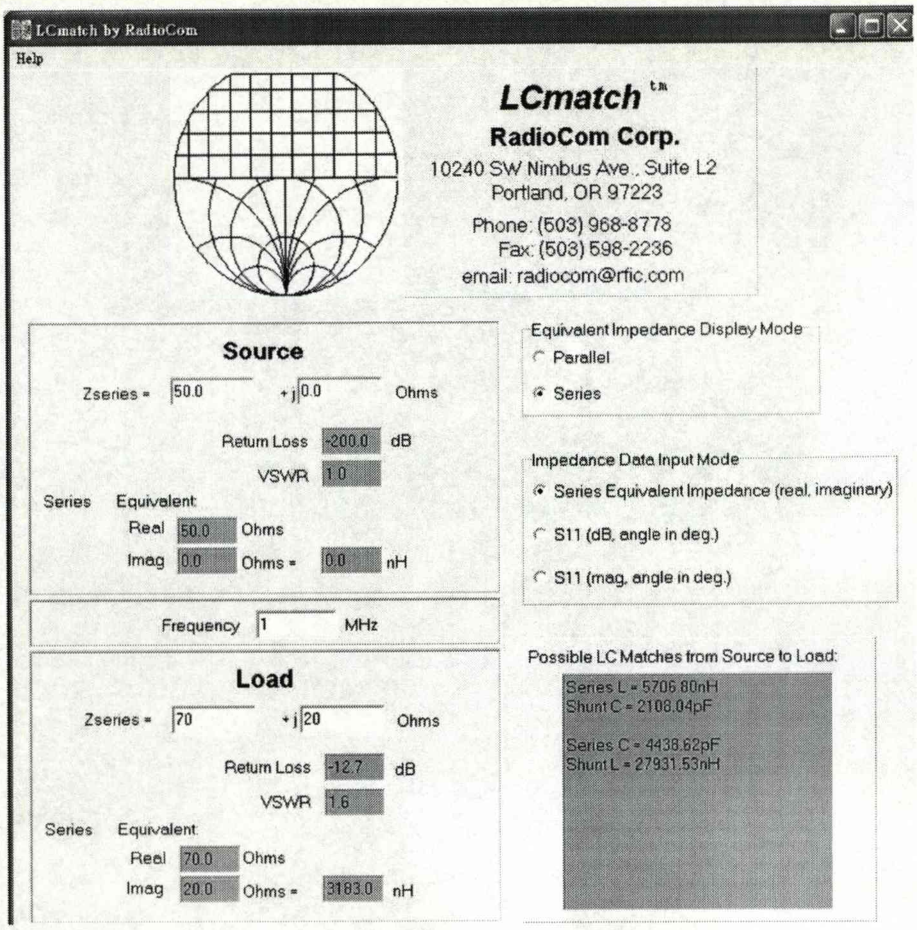


Figure 4.17 The LC match software program [35]

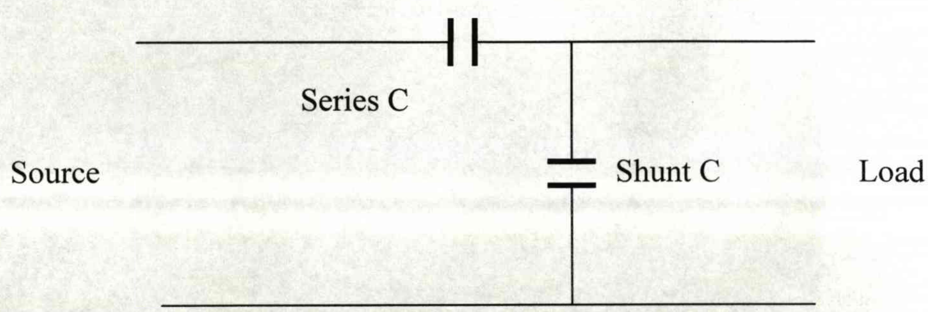


Figure 4.18 The matching circuit

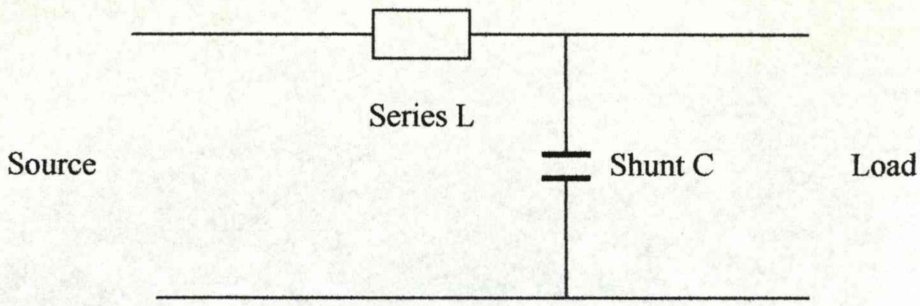


Figure 4.19 The matching circuit

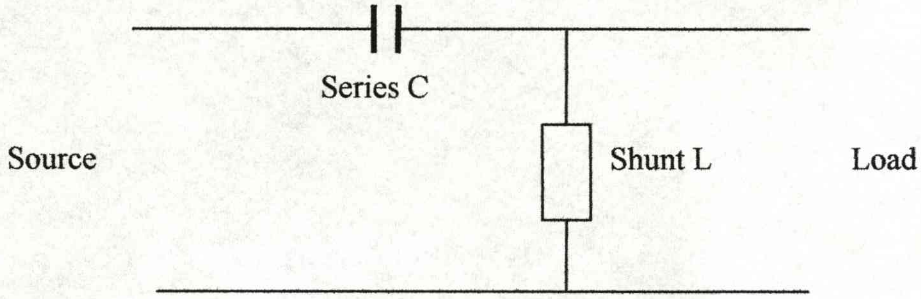


Figure 4.20 The matching circuit

The picture of the constructed matching circuit is shown in figure 4.21 and figure 4.22.

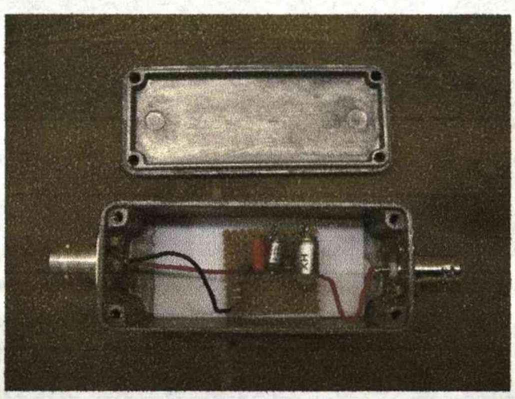


Figure 4.21 and 4.22 The constructed matching circuit with series L = 5706 nH and shunt C = 2108 pF

4.11 Experimental trials

Trials were performed in the laboratory tank, the Albert Dock and the Loch Linnhe. Experimental system in the Albert Dock and the Loch Linnhe (real marine environment) are slightly different from the laboratory tank. In real marine environment, stainless steel receiver and transmitter with a 30 Watt power amplifier were used. Plastic transmitter and receiver were used in laboratory tank.

4.11.1 Measuring the conductivity and temperature of seawater

Before performing the experiments, the conductivity of the seawater was measured by the conductivity meter (Hanna HI 8733) and the temperature of the seawater was recorded by the thermometer in the laboratory tank, the Albert Dock and the Loch Linnhe. These two factors may affect the attenuation of the signal while propagating in seawater so it is important to record them for future comparison of results.

4.11.2 Experiment in the Albert Dock and the Loch Linnhe

Frames were needed to hold the transmitter and receiver in position. Therefore, they could be moved in the seawater during the experiment. Some floats were used to attach to the frames on both transmitter and receiver. It is because the float provides some upthrust force to the frames so that the transmitter or receiver will not be sunk into the sea.

4.11.3 Signal strength against distance experiment in the real marine environment

The system used in the Albert Dock and the Loch Linnhe were almost the same. All the matching of the antenna in both transmitter and receiver were done. After that, the orientations of the antenna in the transmitter and receiver were set. Then it was mounted to the frames with floats. For the receiver, it was connected to the spectrum analyzer (Anritsu MS2711D) which is often used to measure unknown signal characteristics such as carrier level, sidebands, harmonics, etc. Spectrum analyzer is a single channel receiver with a wide range of intermediate frequency (IF) bandwidths for analyzing signal. For transmitter, it was connected to a laptop through optical fibers.

The optical fibers were insulated so that there was no leakage of seawater. Both transmitter and receiver were put into seawater then the orientations of them were aligned. The temperature and conductivity of seawater was recorded. The frequency for transmission was set in the transmitter by the laptop in the experiment. The frequency for transmission was kept constant during the experiment.

The distance between the transmitter and the receiver was zero or 25 cm at the beginning (depending on their antenna orientation). Then the distance between them was recorded and the signal strength was recorded by the spectrum analyzer. The center frequency of the spectrum analyzer was chosen to be the operating frequency for transmission while the span was about 500kHz. The signal strength of the transmitted signal was displayed on the screen with a background noise level. The minimum signal that can be detected is limited by the background noise level which is mainly from the ambient environment when compared to the internal noise generated in the receiving system. After that, with increment of every step of 25cm distance between the transmitter and the receiver, the results were recorded same as before until the signal was lost or reached the other side of the Dock.

The graph of signal strength against distance was plotted. The experiment was repeated by using different frequency for transmission and using matching circuit or without matching circuit. The results were plotted and will be discussed in Chapter 5 Results and analysis.

The picture of receiver with frames and floats are shown in figure 4.23.

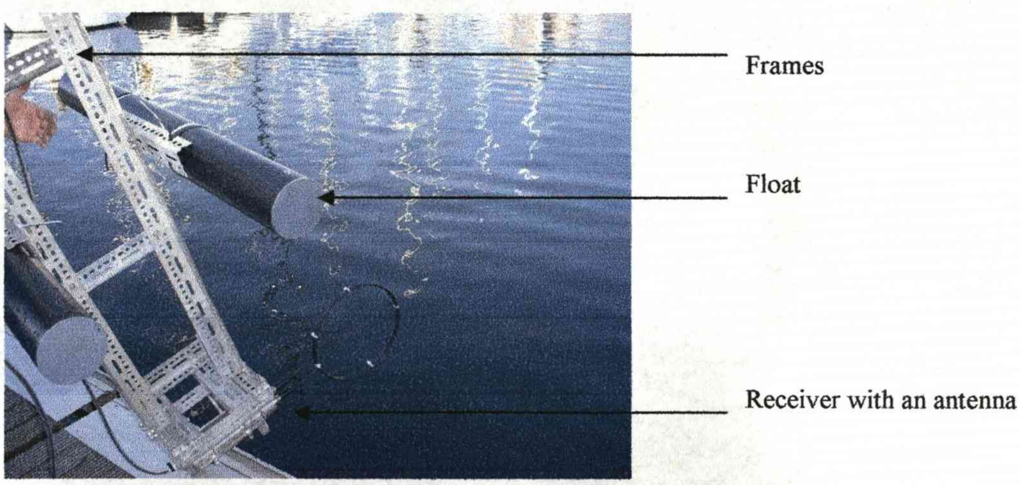


Figure 4.23 The receiver with frames and floats

The picture of transmitter with frames and floats was put into seawater is shown in figure 4.24.

Figure 4.24 The transmitter was put into seawater

4.11.4 Experiment in the laboratory tank

The experiment in tank was similar to the experiment performed in Albert Dock except some equipments used were not the same. The procedures in performing the impedance experiment in Albert Dock were almost the same as performing the experiments in tank.

For the signal strength against distance experiment, it was a little in difference when compared to the experiment in Albert Dock. It is because the limitation of the physical size of the water tank. The length of the water tank is 250cm, the width of it is 200cm and the depth of it is 140cm. Then both transmitter and receiver should be aligned in the center of the water tank. The signal strength recorded by spectrum analyzer when their separation between them was every 10cm apart until the distance between them was about 200cm.

A simple drawing of the laboratory tanks is shown in figure 4.25.

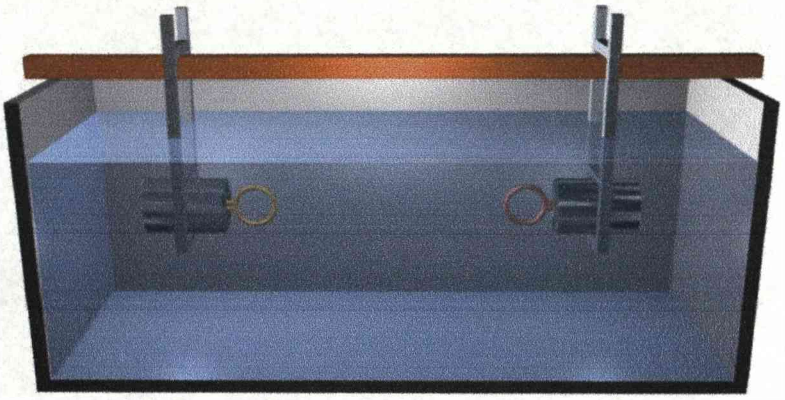


Figure 4.25 The drawing of the laboratory tank

4.12 New design and trials

All experimental results showed that the propagation of EM waves in seawater is possible because the existence of the far field. A new design of launching the antenna in tap water inside a barrel was constructed. The aim is to increase the EM waves generated by water molecules in tap water because conductivity losses are reduced. The picture of the barrel used in the experiment is shown in figure 4.26. The new antenna construction was a parallel wire wires open ended transmission line which was enclosed in a sheathed so that there was no direct contact between the copper wire and tap water. A diagram of the two wire antenna is shown in figure 4.27. The picture of the new transmitter and with the electronic box inside is shown in figure 4.28.

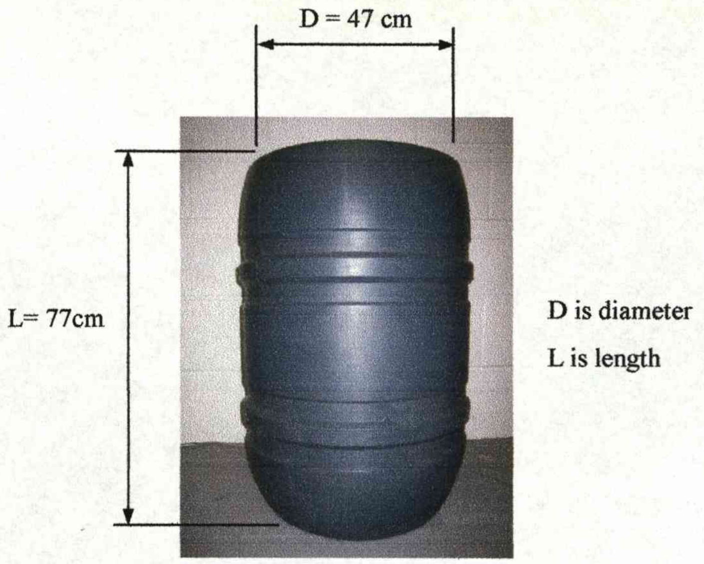


Figure 4.26 A picture of the barrel

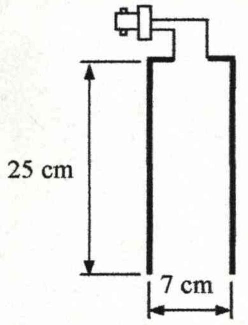


Figure 4.27 Two wires antenna

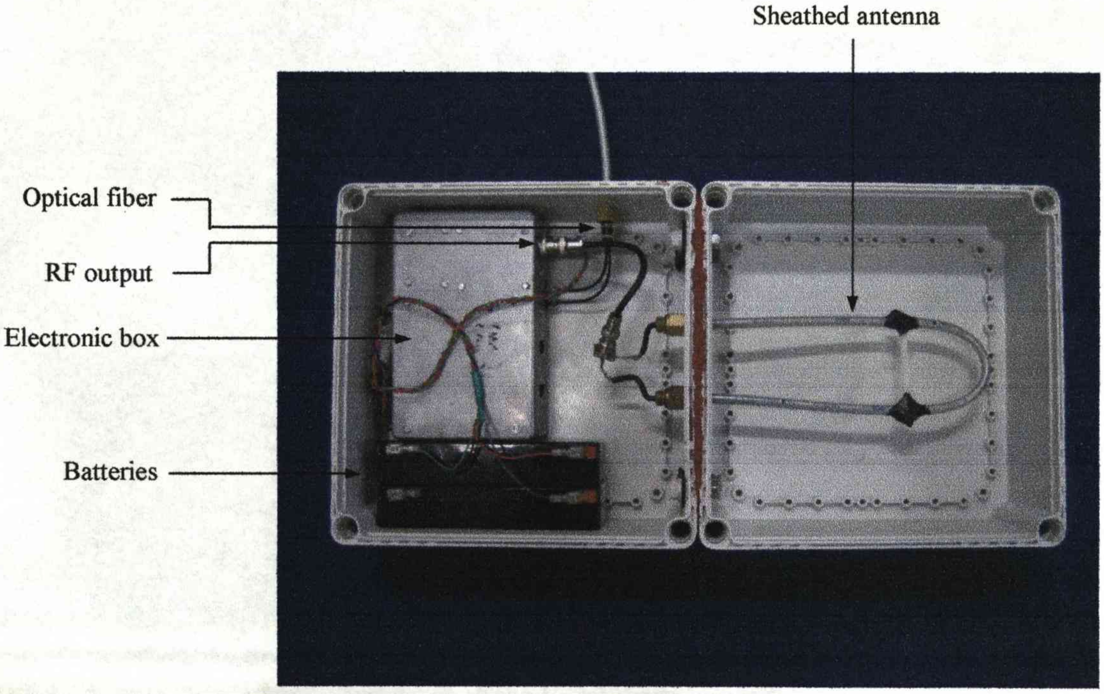


Figure 4.28 The new transmitter with the electronic box and batteries inside.

Trials were performed in the laboratory tank with varied frequency and different antenna at the receiver, one is 32 cm diameter double loop antenna and the other one is two wires antenna. The barrel is filled with tap water and is positioned in the tank which is full of seawater. The seawater and tap water is separated by the barrel so they will not be mixed together. The new transmitter is positioned inside the barrel with tap water and a drawing of it is shown in figure 4.29. A diagram of the whole system for the experiment is shown in figure 4.30. Results of the trials were recorded and will be presented in the Chapter 5.

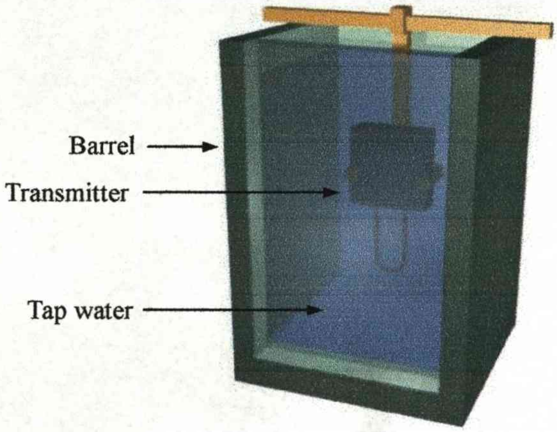


Figure 4.29 A drawing of the transmitter inside the barrel

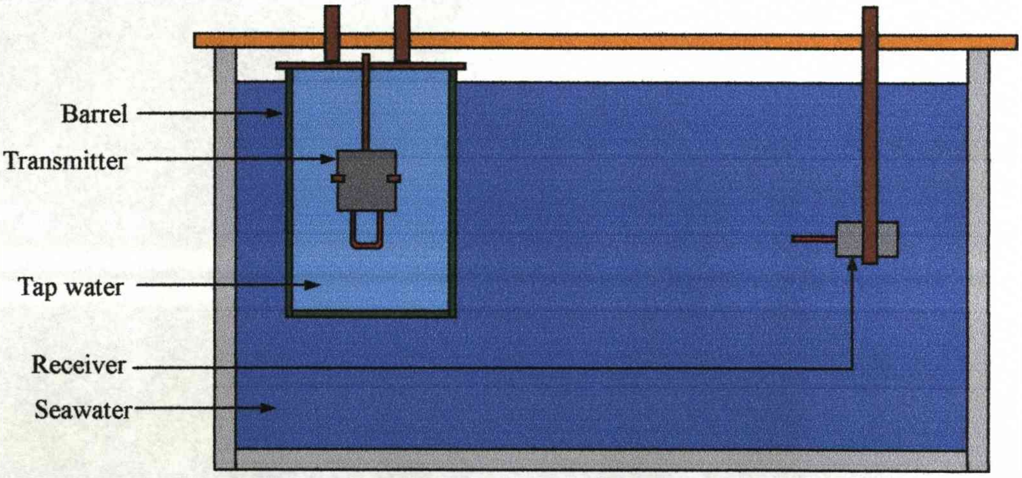


Figure 4.30 The whole system for the experiment

4.13 New design using higher frequency

The maximum output frequency of the DDS is up to 20MHz which limits the trials for higher frequency for propagation in seawater. So a new simple electronic box is built by implementing a crystal oscillator at a fixed frequency. A block diagram of the transmitter is shown in figure 4.31. Filter was used to remove all those higher frequencies so that a sinusoidal waveform can be obtained. 20, 32 and 40MHz crystal oscillators were chosen for signal strength against distance experiments. The switching of frequency needed to be done by manually taking out and opening the transmitter and then replacing the crystal oscillator with another one. Signal strength against distance experiments were performed and results were recorded.

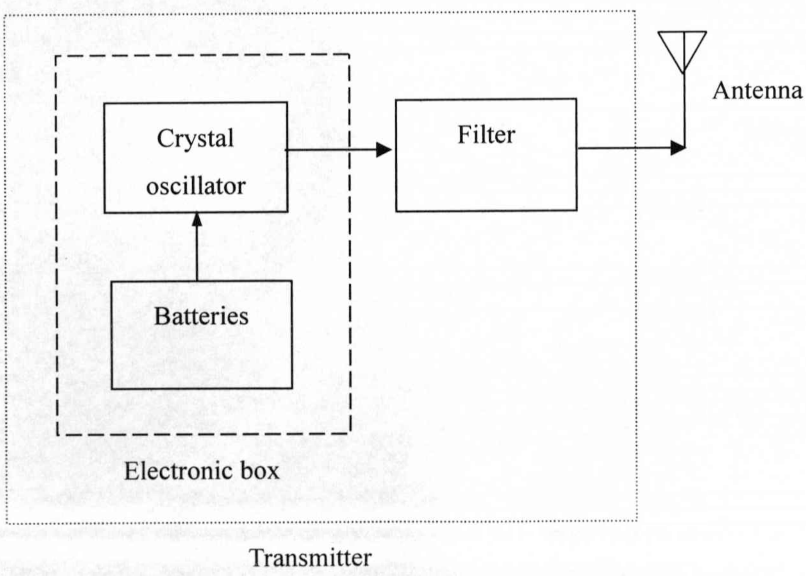


Figure 4.31 A block diagram of the transmitter

4.14 Summary

The methodology for the subsea trials in the laboratory tank, the Albert Dock and the Loch Linnhe have been described in this chapter to assist researchers who wish to pursue similar experiments. All the electronics, equipment and instruments used in the trials and their functions were explained clearly to provide the necessary background information and the theory. A lot of experiments using different methods were undertaken in the laboratory tank and the marine environment to improve the system and to verify that the results obtained were consistent. At the end of the project, a new design which launches the antenna initially in tap water was developed and thoroughly tested in the laboratory tank. Higher signal could be obtained by the receiver antenna having the new design. Trials of high frequency of EM waves for transmission in the laboratory tank were performed with a new electronic circuit which uses crystal oscillator as a signal generator. Trials of the new design in the marine environment are important and a programme of work is being carried by a further research student A. Goudevenos. My detailed experimental results were documented and presented in Chapter 5.

Chapter 5

Results and analysis

Experimental results are initially presented in this chapter, and the detailed analysis is given later in the chapter. Results are taken from the laboratory tank, the Albert Dock, and the Loch Linnhe using conventional antenna. Finally, a new antennae system was developed and results were obtained in the laboratory tank.

5.1 Laboratory tank results

Laboratory tank results were very important for developing and improving the whole system. It saved a lot of time and resources during research which can speed up the project development. Any new ideas or prototypes system were built and tested in the laboratory tank and then modified until the system was reliable and stable before performing trials in the real marine environment. The salinity of the water inside the tank is close to 4 S/m and is specified in the results.

Additional advantage of the tank testing is that the system can be fully tested and modified before doing trials in the real marine environment to reduce the chance of failure.

Disadvantages regarding the limited size of the tank are that signal reflection may occur on the boundaries of the wall of the tank and the static water means that wave fluctuation are low when compared to the ocean.

5.1.1 Antenna orientation in experiments

Different antenna orientations were used in experiments to study the effect on the signal received. For the ease of use, symbols in two dimensional for representing the antenna orientation are used in this chapter. The antenna orientation symbol is the plan view of the transmitter and receiver. These symbols have been shown on the graph of the results to indicate the antenna orientation of the transmitter and receiver when undertaking the experiment. A diagram of the antenna orientation in 3 dimensions and their corresponding symbols are shown in figure 5.1 (two antennae facing each other), 5.2 (two antennae parallel to each other) and 5.3 (two antennae perpendicular to each other).

Figure 5.1 Antennae facing to each other and its symbol

Figure 5.2 Antennae parallel to each other and its symbol

Figure 5.3 Antennae perpendicular to each other and its symbol

5.1.2 Varied frequency results

Results obtain when using a transmitter and receiver constructed as a 32cm double antenna as a function of frequency with different antenna orientation were shown in figure 5.4 and figure 5.5. Results with a transmitter with 24cm double loop antenna and a receiver with 32cm double loop antenna as a function of frequency were shown in figure 5.6 and 5.7. No impedance matching circuits were used with the antenna in order to optimise the signal strength. This is because the purpose of the experiments was to determine the existence of the far field when EM waves are propagating in seawater at high frequency. The different antenna orientations during the experiments were to investigate the properties of the antenna and the signal strength received.

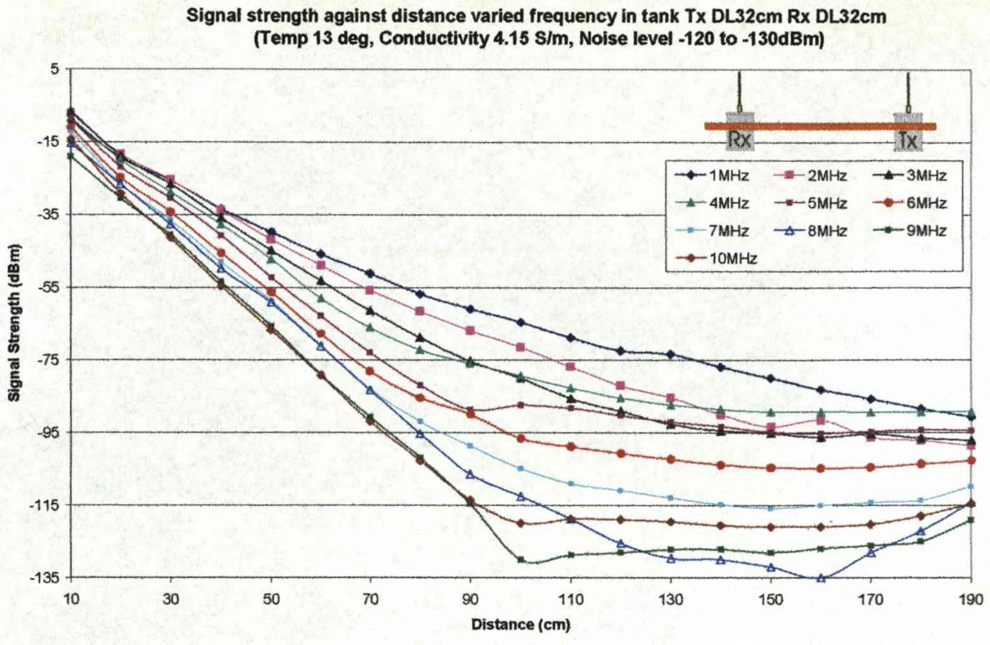


Figure 5.4 The graph of both 32cm diameter double loop antennae of varied frequency

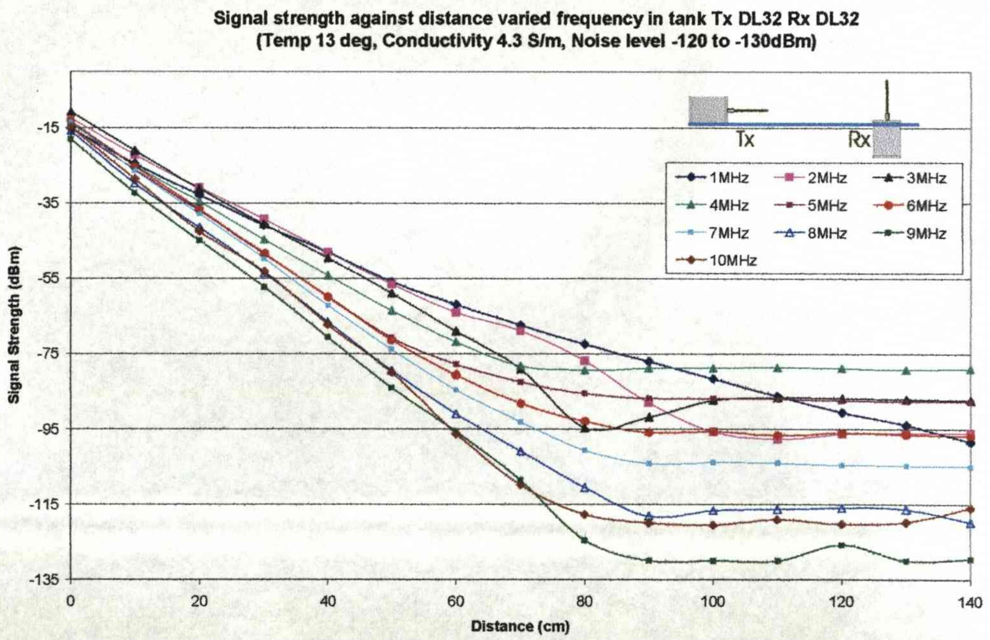


Figure 5.5 The graph of both 32cm diameter double loop antennae of varied frequency

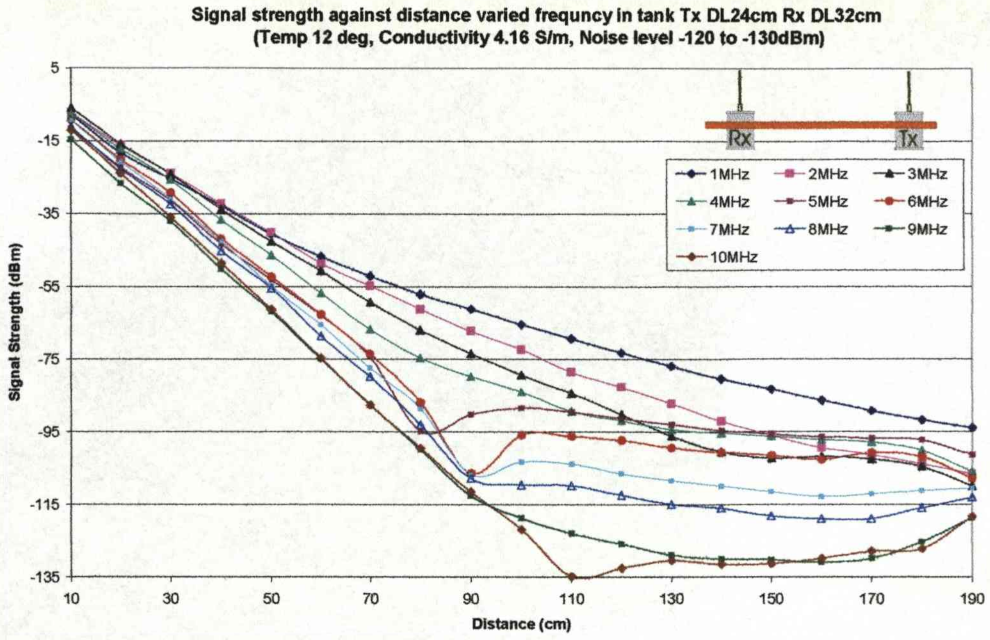


Figure 5.6 The graph of transmitter 24cm and receiver 32cm diameter double loop of varied frequency

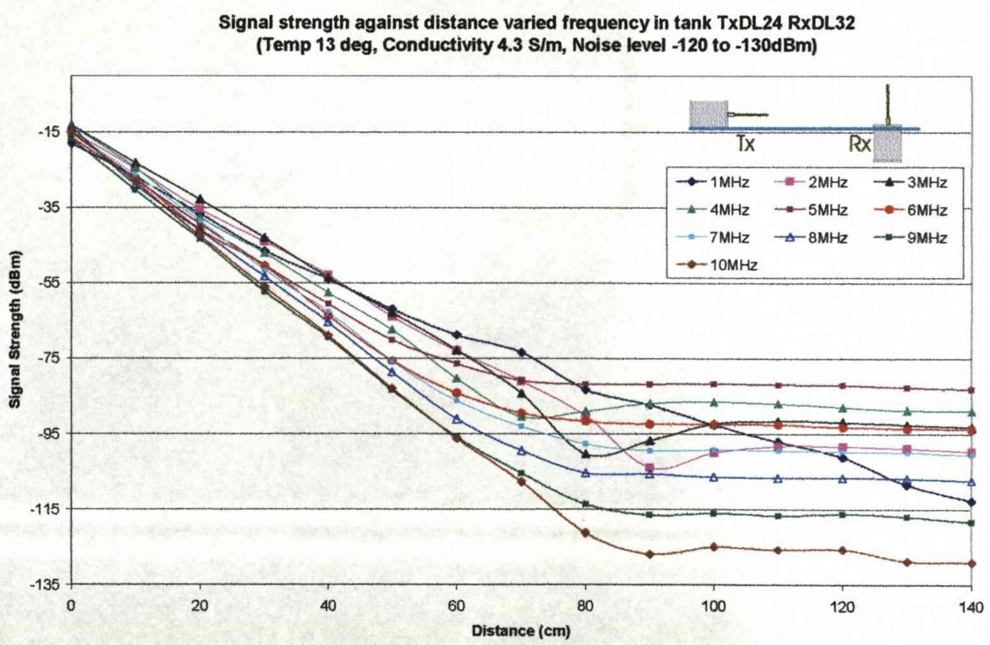


Figure 5.7 The graph of transmitter 24cm and receiver 32cm diameter double loop of varied frequency

5.1.3 Varied frequency results analysis

Figures 5.4 to 5.7, show that there is a clear pattern when the frequency of transmission is increased. The signal rapidly decreases with distance between the antennae. The steepest slope of the curve is in the near field, which obeys the Maxwell's equation when EM waves propagate through conducting medium, the attenuation (α) increases with the frequency and is given by the equation (3.47) in chapter 3:

$$\alpha = \sqrt{\pi \mu f \sigma}$$

where f is the frequency, σ is the conductivity and μ is the permeability of the medium.

Results showed that the signal strength received at the receiver is varied according to the orientation of the antenna. This may due to the fact that the radiation pattern of the loop antenna is directional instead of omni-directional. The loop antenna can be considered by small loop antenna theory and then further reduced to a square loop antenna theory when the maximum dimension is less than about a tenth of a wavelength [31]. A square loop antenna with each size 30cm at 10MHz in the air was simulated using EZNEC software [32]. The geometry for the antenna and the radiation pattern of it in 3 dimensional (3D) and 2-dimensional (2D) are shown in figure 5.8, 5.9 and 5.10. Therefore, the signal strength generated when the antennae are perpendicular to each other as shown in figure 5.5 and 5.7 were higher than when the antennae were parallel to each other as shown in figure 5.4 and 5.6 can be explained by the radiation pattern of the loop antenna obtained from the simulation and the theory of the loop antenna.

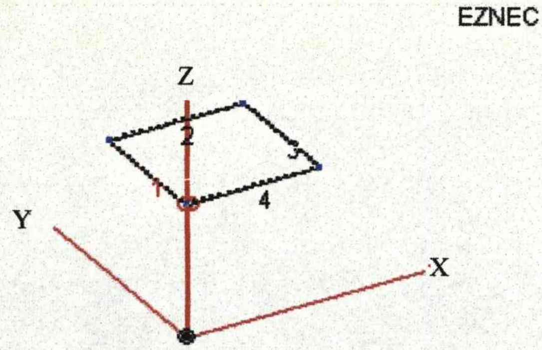


Figure 5.8 The square loop antenna

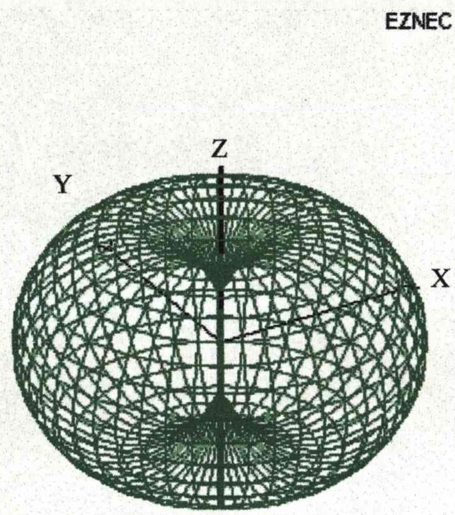


Figure 5.9 The square loop antenna 3 -D radiation pattern

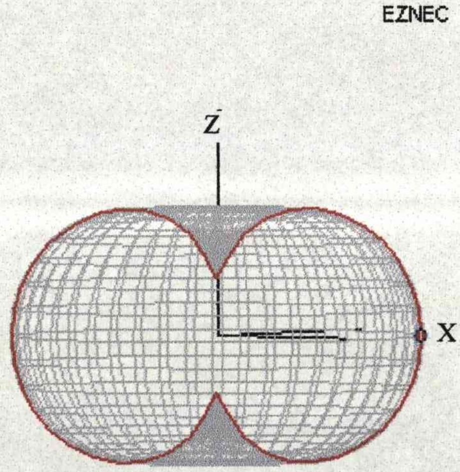


Figure 5.10 The square loop antenna 2-D radiation pattern

From all the results of the signal propagation, EM waves in the range of 1 to 10MHz are highly attenuated in the near field region but have low attenuation in the far field region. However, for the frequency of 1MHz which does not show any far field signal. These results clearly show the existence of a far field region and show the propagation of EM waves at high frequency is possible through seawater. Signal strength received at the receiver at frequency between 3 to 5MHz was higher than the other frequencies. Therefore, this frequency range were chosen for trials in the Albert Dock and Loch Linnhe.

5.2 Real marine environment results

Results taken in the Albert Dock and Loch Linnhe are vital for proving the results in the laboratory tank can be applied in real marine environment. Frequencies within the range of 3 to 5MHz were chosen for the transmission because results in the laboratory tank showed that their performance was better than the other frequencies. Metal transmitter and receiver boxes were used to house the electronics. An extra 30W power amplifier was installed in the transmitter with a net gain of 44dB. Matching circuit was constructed at that particular frequency for transmitting the signal. The purpose of it is to increase efficiency of transferring the power from the power amplifier to the antenna.

5.2.1 Albert Dock results

Trials were carried in the Albert Dock in Liverpool with frequencies at 3MHz, 3.7MHz and 6MHz for transmitting the signal with the antennae facing each other because this orientation gave best results in the laboratory tank. Figure 5.11 showed the results up to the 17m separation between the transmitter and receiver. More results were obtained with further separation distance of transmitter and receiver up to 90m of frequencies ranged from 3.7MHz to 5MHz and shown in figure 5.12. For all the frequencies used, the antennae and signal generator impedance was matched.

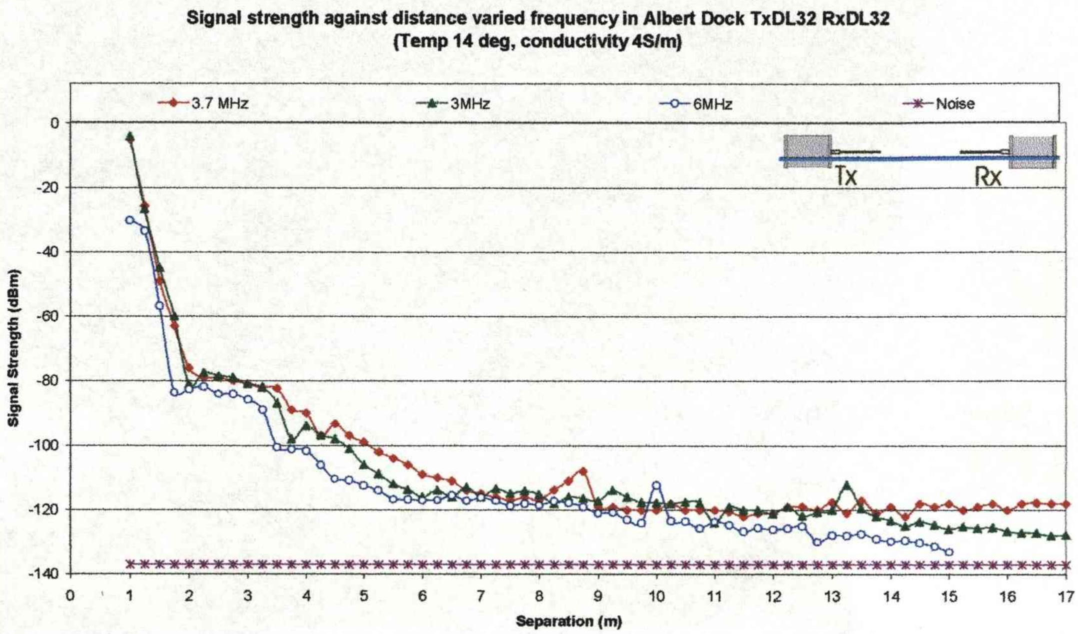


Figure 5.11 The graph of both 32cm diameter double loop antennae of varied frequency

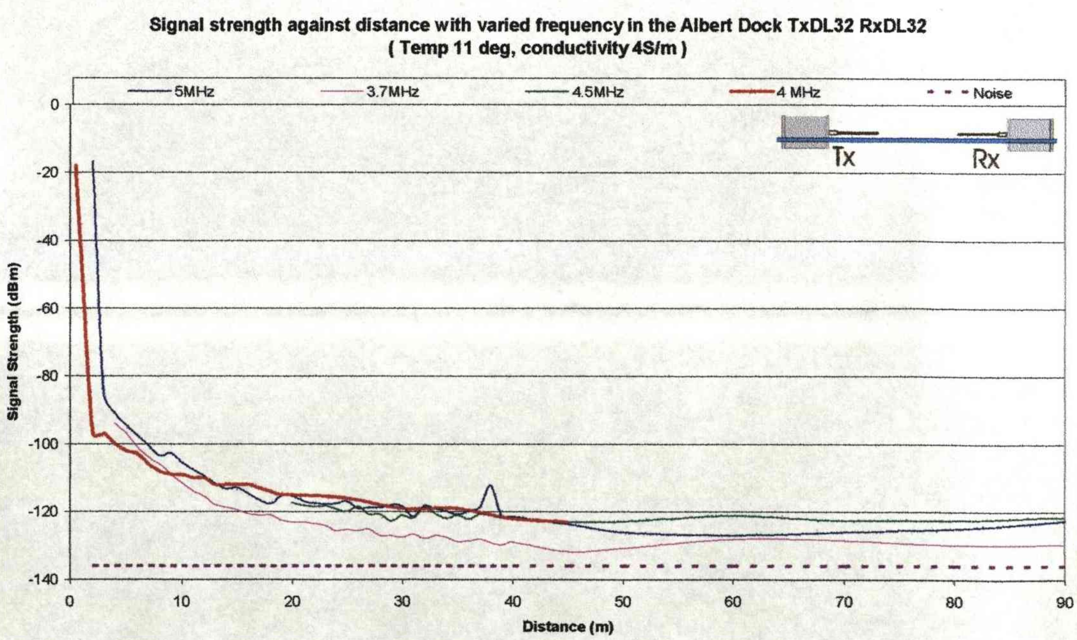


Figure 5.12 The graph of both 32cm diameter double loop antennae of varied frequency

5.2.2 Albert Dock results analysis

Frequencies within the range of 3 to 5MHz worked well in the Albert Dock. Figure 5.11 and 5.12 showed that the far field region does not only exist in the laboratory tank but also in the real marine environment. The signal received at the receiver was about 15dBm above the noise level and propagated up to 90m between transmitter and receiver in figure 5.12.

5.2.3 Loch Linnhe results

Trials were performed at Fort William in Scotland and the antennae were matched at the propagation frequency. Results of different orientation of the antennae at the same frequency at 3.65MHz were shown at figure 5.13 and 5.14. Frequency of 3MHz for transmission with antennae facing each other also recorded and results were shown in figure 5.15. In figure 5.16, results of the antennae were matched at 3.65MHz and the signal strength over a frequency range from 2.4 to 4MHz at the separation of 2m between transmitter and receiver is shown. The purpose of varied frequencies at the fixed distance is to determine the range of the matching circuit as broadband perfect matching in reality is difficult to achieve.

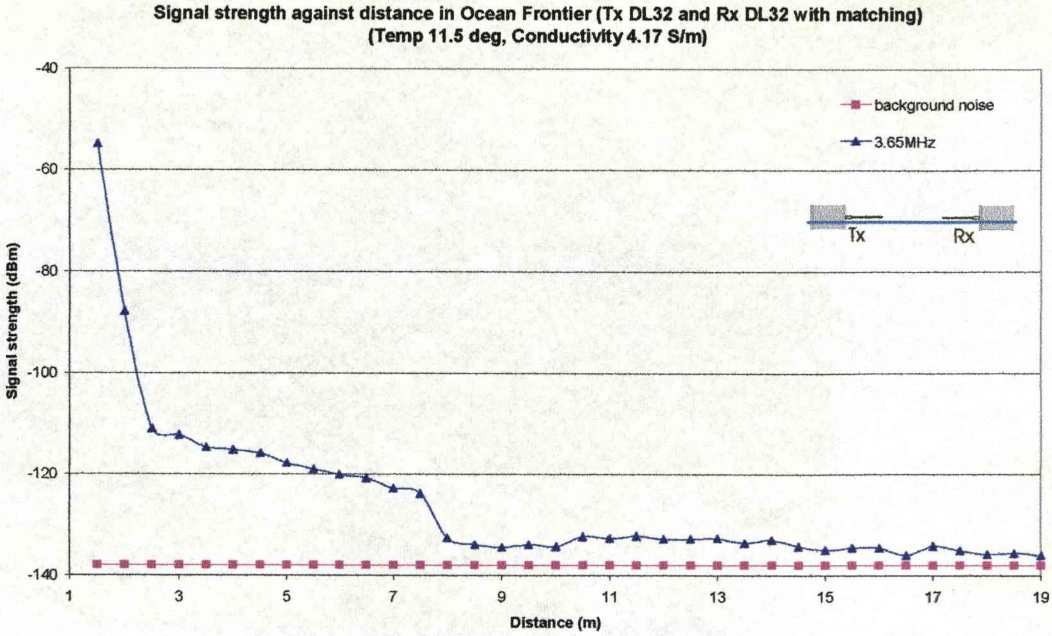


Figure 5.13 The graph of both 32cm diameter double loop antennae at 3.65MHz

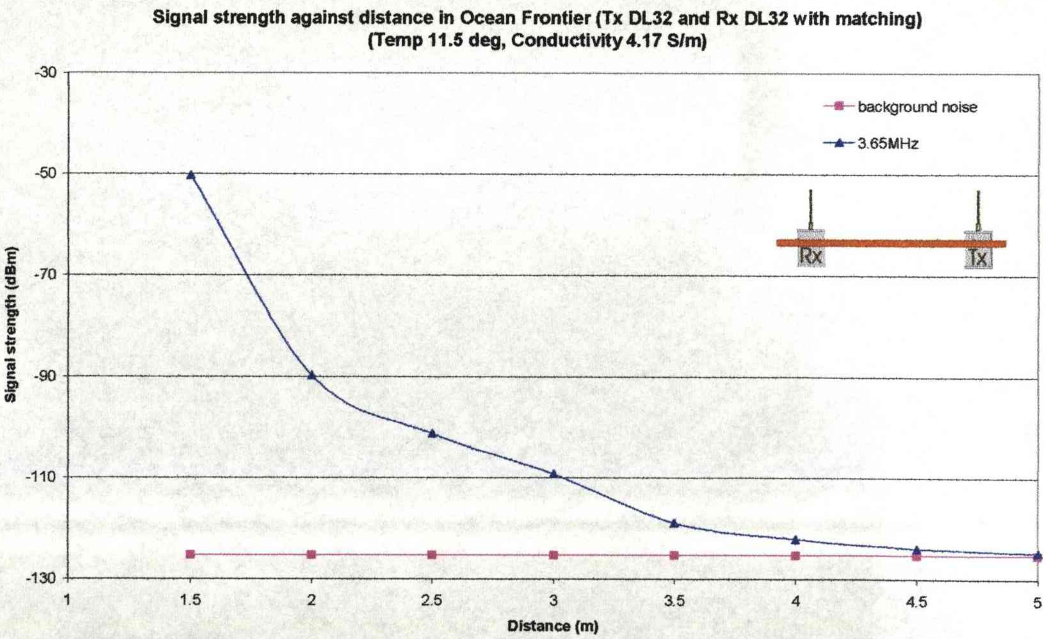


Figure 5.14 The graph of both 32cm diameter double loop antennae at 3.65MHz

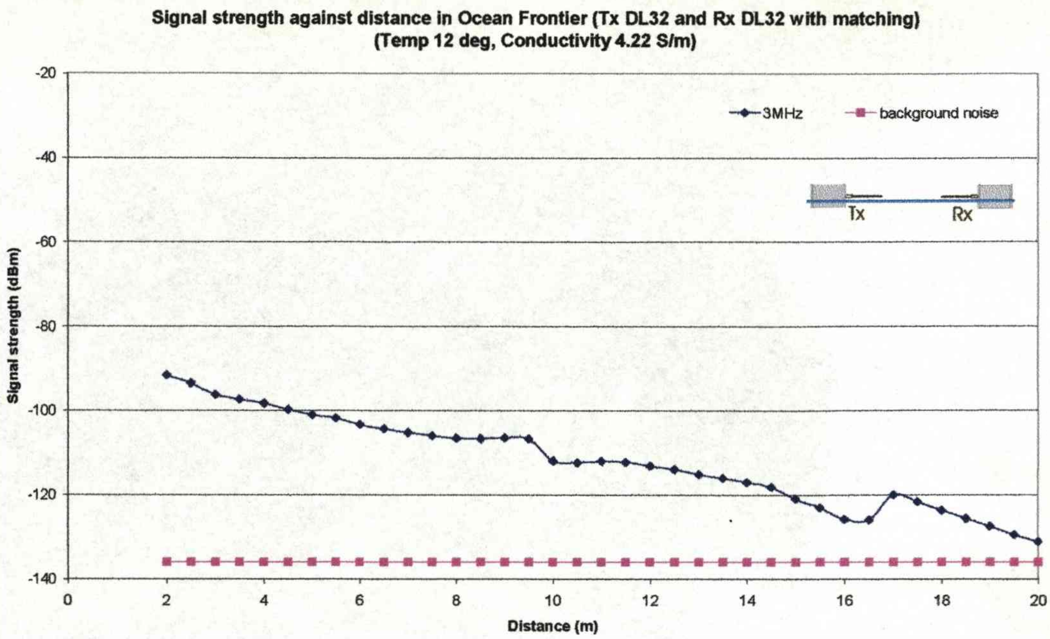


Figure 5.15 The graph of both 32cm diameter double loop antennae at 3MHz

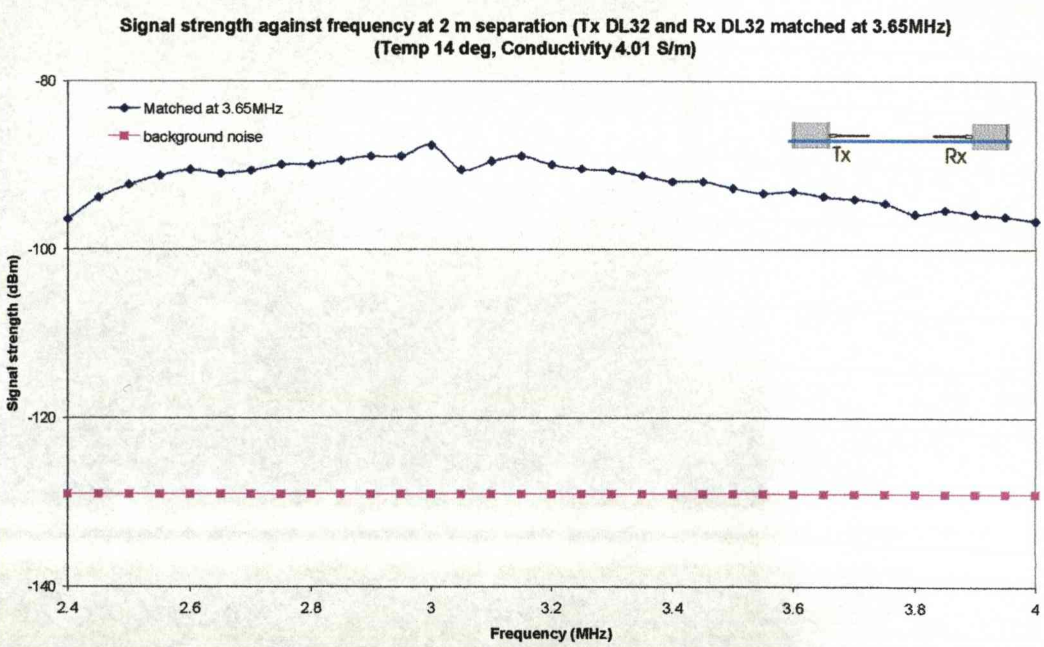


Figure 5.16 The graph of varied frequency at 2m with antennae matched at 3.65MHz

5.2.4 Loch Linnhe results analysis

Results in figure 5.13, 5.14 and 5.15 are consistent with the Albert Dock and the laboratory tank results. The antennae facing each other orientation has better performance than the antennae parallel to each other. Signal can be received over 20m in separation between the transmitter and receiver. Results in figure 5.16 showed that the signal strength received at about 3MHz is the strongest within the frequency range from 2.4MHz to 4MHz even though the antennae were matched at 3.65MHz. This is because the perfect matching in practical is hard to achieve due to the fact that the matching circuit is constructed from inductors and capacitors. Some of the values of the capacitors and inductors calculated can not be purchased from the electronics supplier so the nearest value has to be chosen to construct the required circuit, also slight variations in the value of the product may be introduced during manufacturing. Hence the matching circuit built may have a frequency slightly shifted from the originally design and not perfectly matched. The results in figure 5.16 also show the frequency range of the matching circuit. The signal strength received decreased when the frequency was shifted away from the matched frequency. Therefore, the matching circuit is selective and only allows the matched frequency range to pass through and other frequencies will be attenuated further.

5.3 The new system results in the laboratory tank

A new design of the antenna and system was developed. The antenna was immersed in tap water inside a bucket and then the bucket was immersed in seawater. So the antenna was launch in the tap water inside the bucket and the EM waves propagated through the tap water and the wall of the bucket before reaching the seawater. Trials were performed in the laboratory tank and results were recorded.

5.3.1 Varied frequency results without matching

Trials were performed in the laboratory tank with the new antenna design. The frequency range of 2 to 10MHz was selected for transmission. Transmitter was using the two 20cm wires in all trials but two kind of receiver antenna design were used for comparison. Results of 32cm diameter double loop antenna in the receiver was shown in figure 5.17 and 20cm wires antenna in the receiver was shown in figure 5.18. No matching circuit was constructed at the transmitting frequency because the aim is to investigate the performance of the new antenna design before modification.

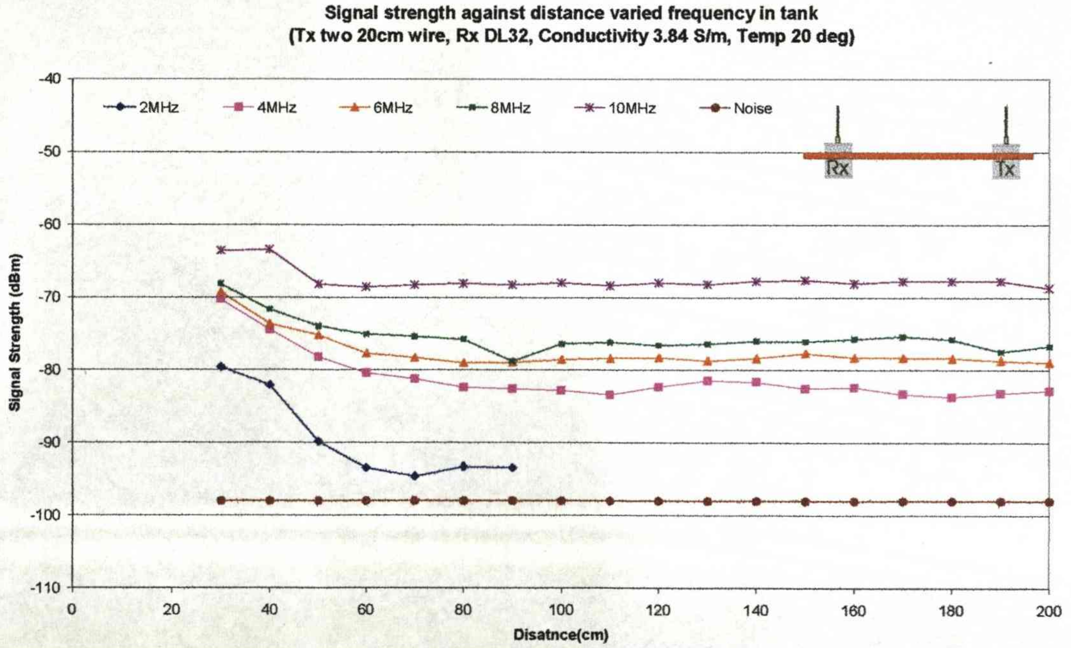


Figure 5.17 The graph of varied frequency with 32cm double antenna at the receiver

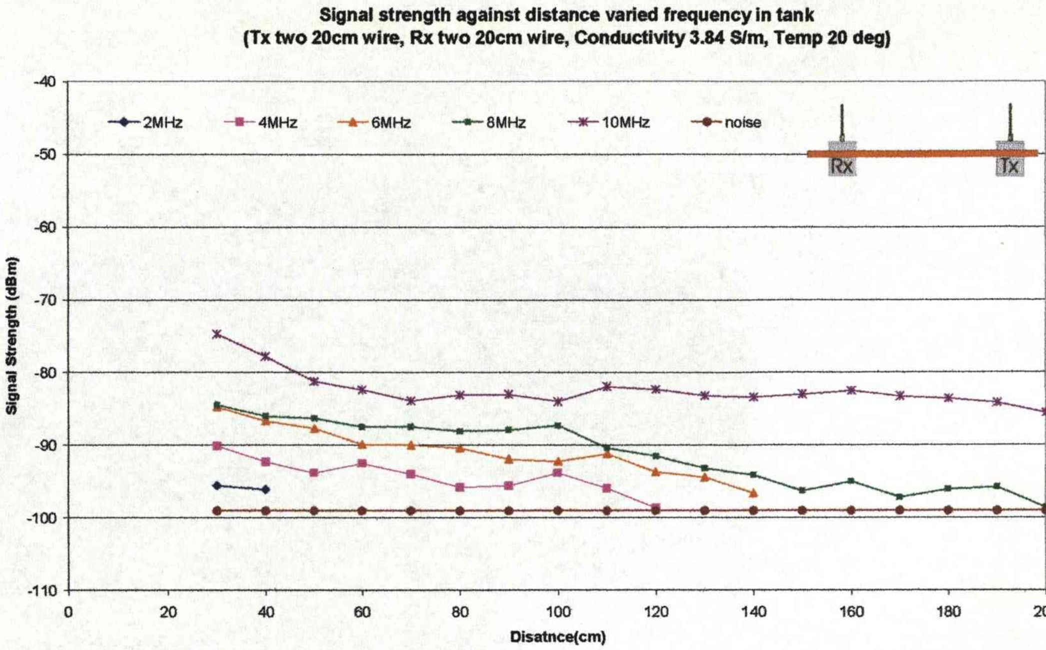


Figure 5.18 The graph of varied frequency with two wires antenna at the receiver

5.3.2 Varied frequency results analysis

Results in both figure 5.17 and 5.18 showed that when the frequency increases the signal strength received increase and reached maximum at 10MHz. The signal transmitted at 2MHz frequency can only propagate a short distance. The double loop antenna received signal about 10dBm stronger than the 20cm wire antenna in all frequencies. The attenuation of double antenna receiver is smaller than the 20cm wire antenna receiver because the curves in figure 5.17 are flatter than the curves in figure 5.18.

When the results obtain in the new system in figure 5.17 and 5.18 are compared to the results in figure 5.4 and 5.6, the performance of the new antenna design with 20cm wire as a transmitter antenna launched in tap water is better than the double loop antenna launched in seawater. The attenuation in the near field is greatly reduced when the slope are compared. The signal strength received for all frequencies are increased except the 2MHz. At 10MHz, the signal strength improved by about 50dB. This 50dB gain is costly when using a power amplifier. But when the antenna is launched in tap water, the EM radiation is generated by the dielectric dipole water molecules and propagates through seawater which is a better method than using the power amplifier as it is cost effective and the transmitter consume less power from the batteries that means it can be operated for a longer time. These trials successfully demonstrated that EM radiation is generated by the dielectric dipole water molecules which are able to propagate through seawater with low attenuation and results in generating a stronger signal strength at the receiver.

5.3.3 Results of after matching

The matching plays an important role in transmission line and antenna because it determines the efficiency of the power transmitted to the antenna from the transmission line. Two set of experiments were designed and performed. The first experiment was without having any matching circuit constructed between the signal generator and the antenna. In the second experiment, the antenna was matched to the signal generator with a matching circuit constructed in between. Frequency at 10MHz was chosen to be the transmitting frequency during these experiments.

The Smith Chart, the impedance scan from 1 to 20MHz and VSWR of the antenna without matching are shown in figure 5.19, 5.20 and 5.21. After matching circuit was introduced between the antenna and signal generator, results are shown in figure 5.22, 5.23 and 5.24.

Laboratory tank trials for the two wire antenna transmitter without matching and after being matched were measured to obtain the signal strength received in the tank as a function of the distance between the transmitter and receiver. Results with the 32 cm double loop receiving antenna is shown in figure 5.25 and with the two wires receiving antenna is shown in figure 5.26.

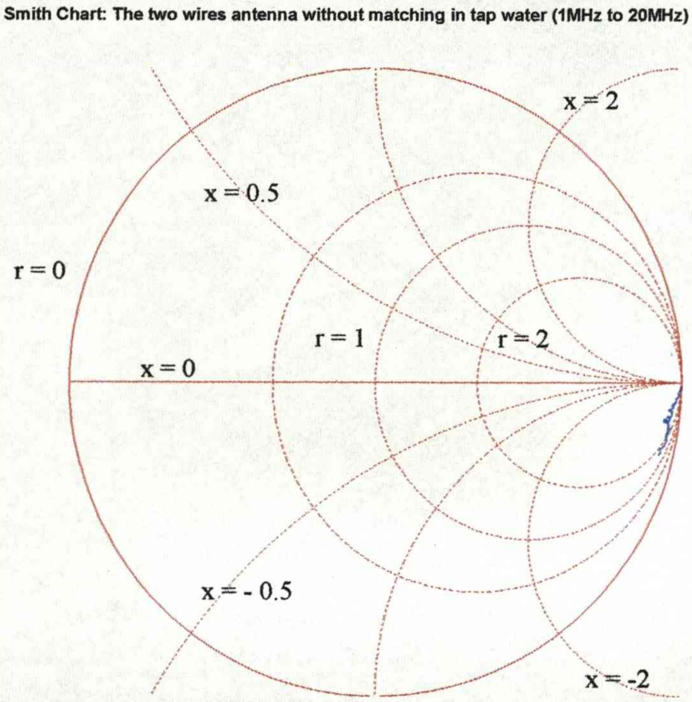


Figure 5.19 The Smith Chart of the two wires antenna without matching in tap water

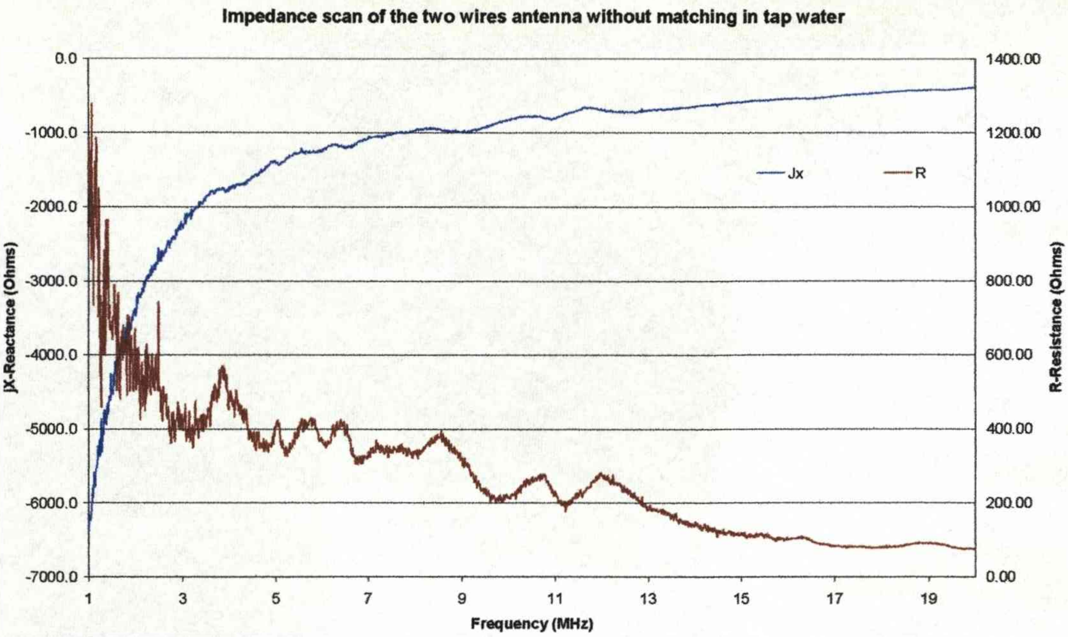


Figure 5.20 The impedance scan of the two wires antenna without matching in tap water

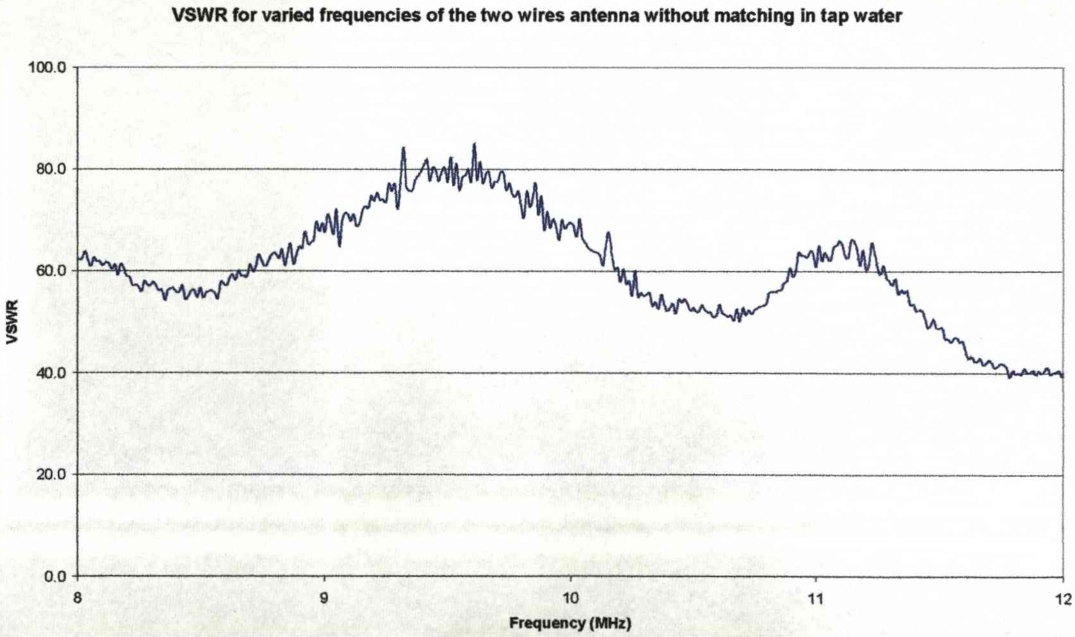


Figure 5.21 The VSWR of the two wires antenna without matching in tap water

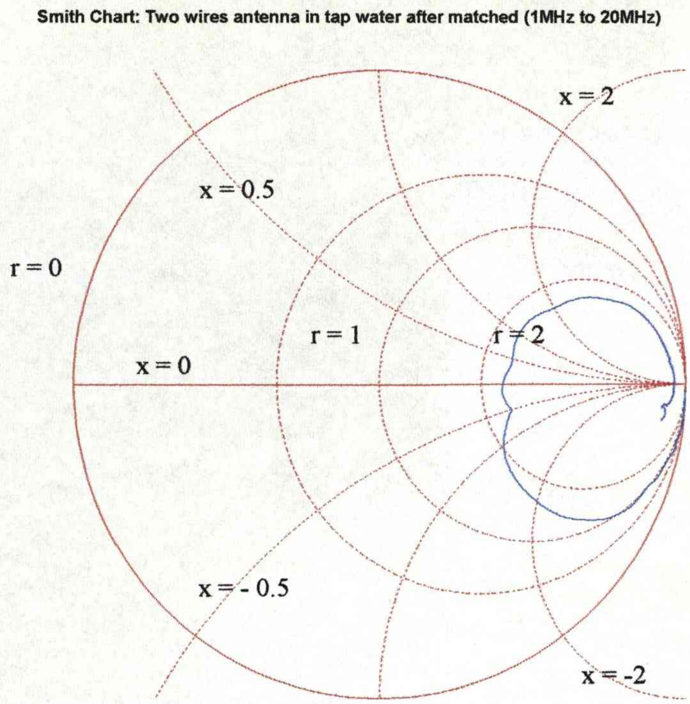


Figure 5.22 The Smith Chart of the two wires antenna in tap water after matched

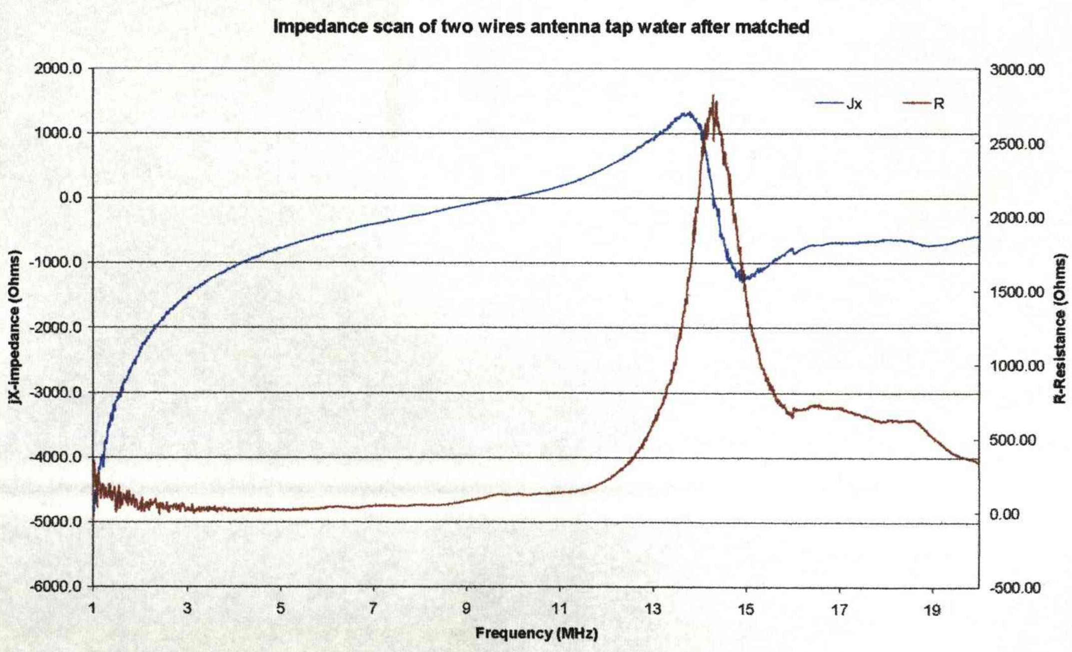


Figure 5.23 The impedance scan of the two wires antenna in tap water after matched

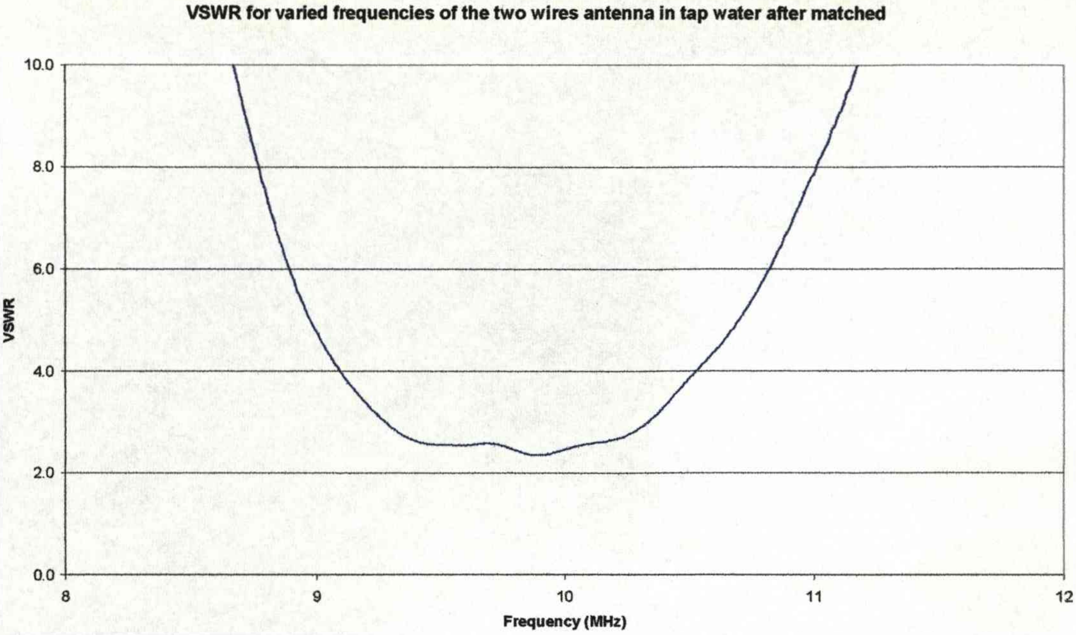


Figure 5.24 The VSWR of the two wires antenna in tap water after matched

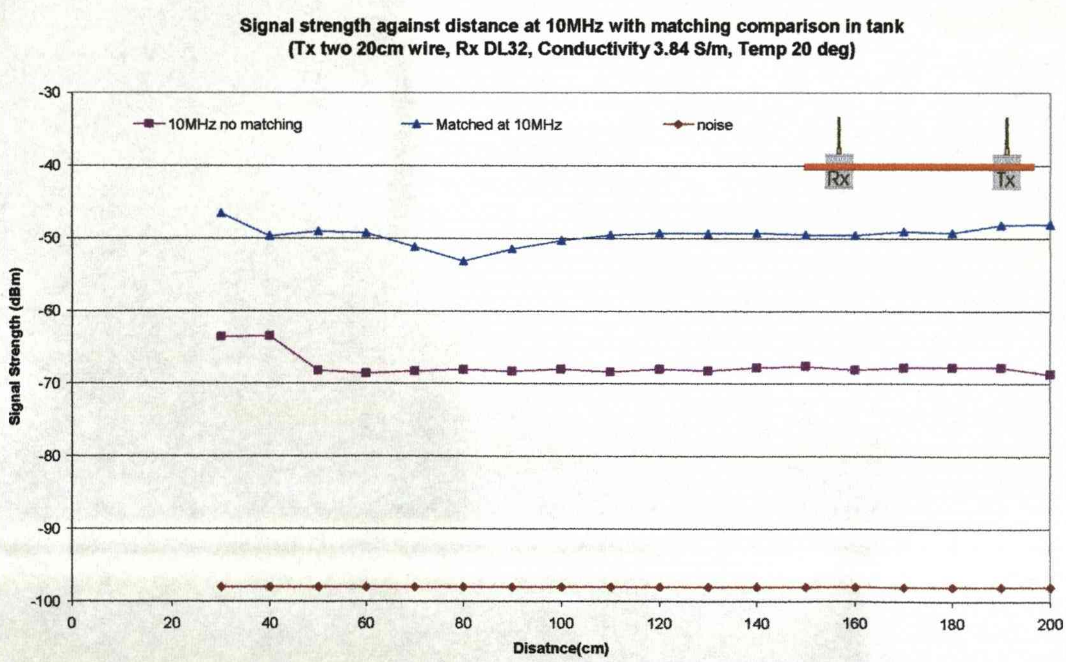


Figure 5.25 The graph of matching comparison with 32cm double loop antenna at the receiver

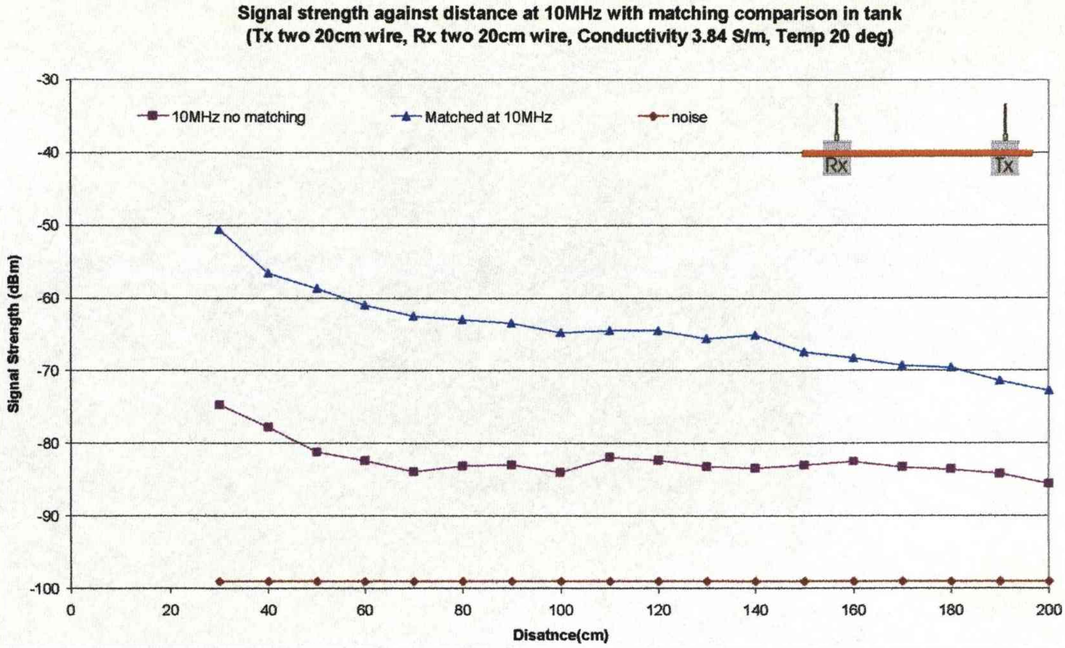


Figure 5.26 The graph of matching comparison with two wires antenna at the receiver

5.3.4 Analysis of the results after matching

When the results given in figures 5.25 and 5.26 are compared, the 32cm double antenna as a receiver has a better performance than the two wires antenna because the results in figure 5.25 have less attenuation and the signal strength is higher than the curves in figure 5.26.

In these experiments, the only difference is the matching circuit while other variable were kept the same. So the increase in signal strength is contributed by the matching of the antenna. There is about 18dB gained by simple applying the matching circuit. This shows that the matching is vital in underwater communications when using the new antenna design and can increase the efficiency of the whole system.

5.3.4.1 PSpice simulation analysis

From the data in the Smith Chart shown in figure 5.19, the antenna at 10MHz was modelled into equivalent circuit of a resistor (R_a) in series with a capacitor (C_a). The source is a signal generator with 50 ohms output hence the equivalent circuit is a 50 ohm resistor and a sinusoidal generator. The coaxial cable is very short when compared to a tenth of wavelength of transmission at 10MHz (wavelength at 10MHz is 20m) so it can be eliminated. The whole equivalent circuit diagram before matching was modelled in PSpice and is shown in figure 5.27. The matching circuit at 10MHz was designed by LC match software and added between the antenna and signal generator in the PSpice diagram in figure 5.29

The PSpice simulation was carried out to investigate the performance of the matching circuit theoretically and the power fed into the antenna before matching and after matching with varied frequencies was obtained in figure 5.28 and 5.30 will be compared to the results obtained practically in tank in figure 5.25 and 5.26.

In figure 5.28, at 10MHz, the power fed into the antenna is 28.2mW. In figure 5.30, at 10MHz, the power fed into the antenna is 503.9mW.

Power gained in dB after matching = 10 log(503.9m) – 10 log(28.2m)

= 12.52dB

The signal gain was about 18 dB in figure 5.25 and 5.26 after matching compared to the simulation results 12.52 dB. There is about 5.48dB in difference, but the most important is to prove that the matching can improve the power efficiency of the whole system. Also as shown in figure 5.30, when the circuit is matched at 10MHz, the power fed into the antenna is at the peak level at 10MHz while other frequencies for transmission will result in power loss due to not perfectly matched.

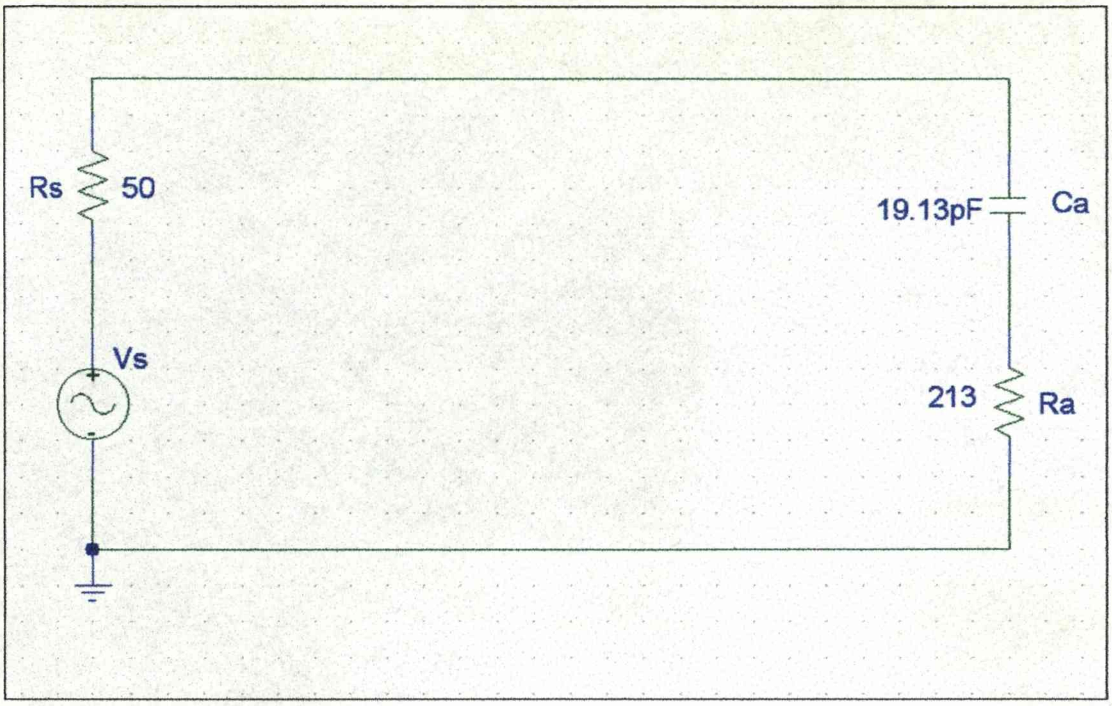


Figure 5.27 The equivalent circuit diagram of the system in PSpice

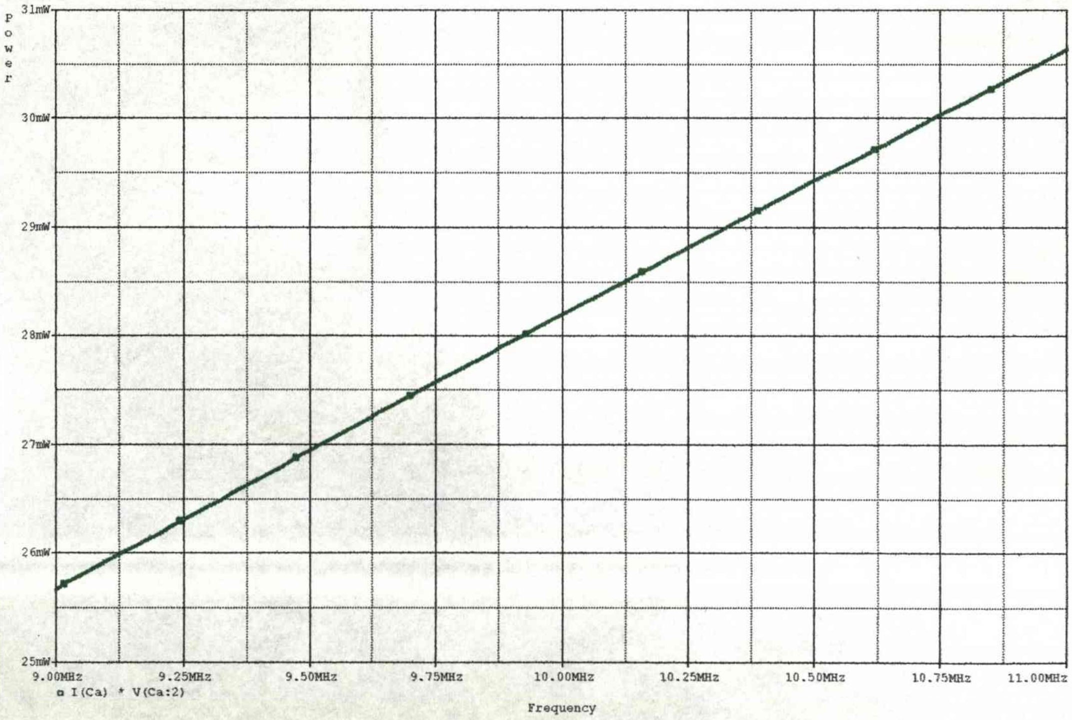


Figure 5.28 The power feed into the antenna before matching in PSpice simulation

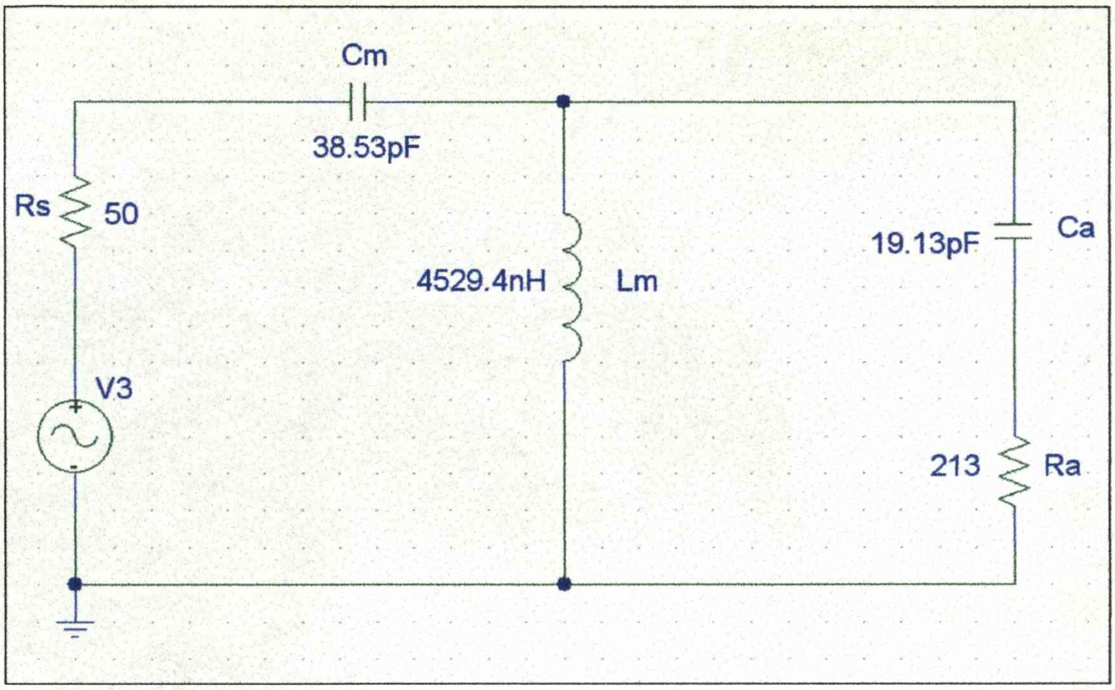


Figure 5.29 The equivalent circuit diagram of the system after matching in PSpice

Figure 5.30 The power feed into the antenna after matching in PSpice simulation

5.3.4.2 Theoretical calculation analysis

The VSWR before matching in figure 5.21 is about 69.6 and the VSWR after matched in figure 5.24 is about 2.5.

The reflection coefficient is, $|\Gamma| = \dfrac{VSWR - 1}{VSWR + 1}$

Before matching,

$$|\Gamma| = \frac{69.6 - 1}{69.6 + 1} = 0.9717$$

The transmitted power to the antenna before matching is, $P_{T1} = \left(1 - |\Gamma|^2\right)P_i$,

where P_i is the power from the signal generator in Watts.

$$P_{T1} = \left(1 - (0.9717)^2\right)P_i = 0.05585P_i$$

After matching,

$$|\Gamma| = \frac{2.5 - 1}{2.5 + 1} = 0.4286$$

The transmitted power to the antenna after matching is, $P_{T2} = \left(1 - |\Gamma|^2\right)P_i$

$$P_{T2} = \left(1 - (0.4286)^2\right)P_i = 0.81632P_i$$

The power gained after matching is:

$$P_{gain} = \frac{P_{T2}}{P_{T1}}$$

$$\frac{P_{T2}}{P_{T1}} = 10\log\left(\frac{P_{T2}}{P_{T1}}\right)dB = 10\log\left(\frac{0.81632}{0.05585}\right)dB$$

$$P_{gain}(in\ dB) = 11.65dB$$

If the VSWR = 1, perfectly matched then:

$$|\Gamma| = 0$$

$$P_{T2} = \left(1 - |\Gamma|^2\right) P_i$$

$$P_{T2} = P_i$$

$$P_{gain} = \frac{P_{T2}}{P_{T1}}$$

$$\frac{P_{T2}}{P_{T1}} = 10\log\left(\frac{P_{T2}}{P_{T1}}\right) dB = 10\log\left(\frac{1}{0.05585}\right) dB$$

$$P_{gain} = 12.53 dB$$

The power gained after matching using theoretically calculation is 12.53dB, which is exactly the same as the results from the PSpice simulation given at the beginning of section 5.3.4.1

5.3.5 Higher frequency for transmission

The limitation of the DDS generator is the maximum frequency cannot go higher than 20 MHz. Therefore, a new electronic box using crystal oscillator as a generator was built. 20MHz, 32MHz and 40MHz crystal oscillators were used for transmission during trials. Filters were used to filter out all those higher harmonics than the fundament frequency to give a desired sinusoidal waveform output. No matching circuit was used in trials. The objective was to investigate the effect of higher frequency of EM waves propagation in seawater.

5.3.5.1 Results at higher frequency for transmission

Trials undertook with the new system except the electronic box was replace by the new crystal oscillator electronic box. The antenna at the transmitter was a two 20cm wires and the antenna at the receiver was a 32cm diameter double loop. Results of the signal strength against distance was shown in figure 5.31.

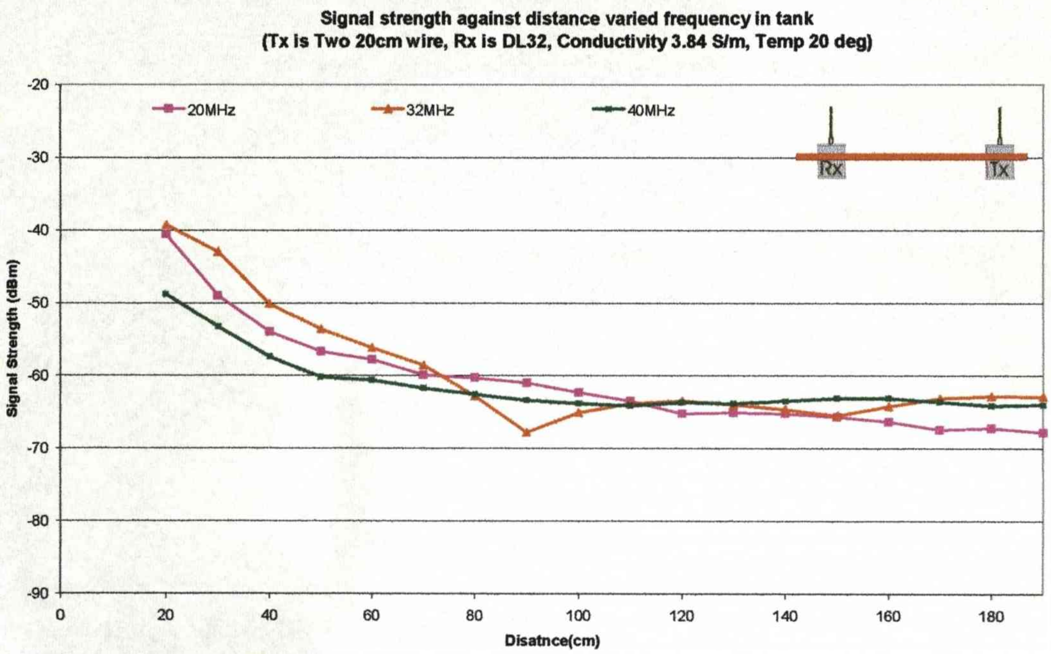


Figure 5.31 The graph of signal strength with varied frequency in tank

5.3.5.2 Analysis of results at higher frequency for transmission

When figure 5.31 is compared to figure 5.17, it showed a similar pattern of having a low attenuation at the far field. Results were consistent and the signal strength received increases with frequency up to 32MHz. The signal strength received of 32MHz and 40 MHz transmission were almost the same.

5.4 A summary of results analysis

All results in the laboratory tank, the Albert Dock and the Loch Linnhe show that the propagation of EM waves in seawater is possible at MHz because the existence of far field. The problem is when the signal is received is close to the background noise level, it cannot be distinguished and will be lost.

The implementation of the matching circuit between the signal generator and the antenna can increase the power emits from the antenna. Hence, the signal received at the receiver will be increased. Results of the matching obtain in trials matched with the theory which show an improvement when the matching circuit is introduced. The VSWR is the term used to describe the matching performance in the circuit. In reality, VSWR in the range of 1 to 3 is acceptable and ideally, VSWR equals to 1 will be perfectly matched without any reflection or power loss but hard to achieve in practical.

Results of the new system design in launching the antenna in the tap water show that the signal strength received increased when compared to the antenna launching in the seawater directly. Results of the new system with a higher frequency at 20, 32 and 40MHz for transmission shows that the signal strength increases with frequency up to 32MHz when compared to the results of the new system transmitted at 4 to 10MHz. These results support the EM waves radiation generates by dipole oscillation of the water molecules within the electric field.

Chapter 6

Conclusion and future work

A summary and the achievements of the project will be given. Then the application of this project will be discussed and finally, suggestions will be given for further investigation of the work in the future to improve the system.

6.1 Project summary

EM wave propagation (at MHz) in seawater were studied. The seawater is conductive and has 4 Sm^{-1} so the signal transmitted at that frequency range will suffer a high attenuation and propagate a short distance. In the near field, the attenuation of signal strength is high so it seems that the signal strength will rapidly decrease to the noise level as the distance increases. We would expect that eventually, the signal cannot be distinguished from the noise. But when the signal reaches the far field, some signal strength is found to be present and the signal only decreases slightly or remains almost constant depending on the frequency for transmission to longer distances. This is because the generation of EM waves by the dipole oscillations of the water molecules within the antenna electric field. This factor makes EM waves propagation in seawater possible.

In this project, the frequency generator is using the direct digital synthesizer as the source, which can be changed instantly in the laptop outside the transmitter. Signal is then pre-amplified by a low noise amplifier. Then a low pass filter is used to block the spurious signal generated by the DDS and the frequencies not interested in. After that, the power amplifier is used to boost up the signal (for the trials in the Albert Dock and the Loch Linnhe). Finally, the signal is fed to the antenna for emitting the EM waves in the seawater. Receiver is designed to pick up the weak signal from the transmitter and then analysed by the spectrum analyser. The transmitter and receiver are both working properly in the laboratory water tank, the Albert Dock and the Loch Linnhe.

Signals can be received and detected by an Anritsu spectrum analyser. Various frequencies, different types of antennae (for example, single loop antennae, double loop antennae and quad loop antennae with different diameter were made) and orientation of antennae for transmission also performed. Results were recorded and graphs were plotted. It was found that the double loop antenna had the best performance among them. Comparison of results from the water tank, the Albert dock and the Loch Linnhe was done. It can be concluded that the far field is not only existence in the water tank in laboratory but also in real marine environment.

A new design was developed in launching the antenna in tap water inside a barrel which is used to separate the seawater from having direct contact with the antenna and the tap water. The results of the new system had improved the performance and the signal received at the receiver had increased about 10dB to 50dB depending on the frequency for transmission. The attenuation in the near field was reduced by this new system too.

The matching of the antenna and the signal generator in the transmitter was done by introducing a matching circuit in between. When the antenna and the signal generator were matched, the signal strength received at the receiver is further increased.

Finally, trials in the laboratory tank at frequencies 20MHz to 40MHz for transmission were performed. EM waves over 20MHz should suffer a huge attenuation while propagation in seawater but results showed that the attenuation in the far field is still low even when the frequency was up to 40MHz. Summing all results, the propagation of EM waves is generated by the dipoles oscillation of water molecules.

6.2 Achievement

The achievements in this project are listed as below:

1. Carried out trials in real marine environment in the Albert Dock and the Loch Linnhe.
2. A new design in launching the antenna in the tap water of the transmitter increased the signal strength received at the receiver by 50dB at 10MHz when compared the antenna launched in seawater (see section 5.3.2).
3. Matching of the antenna and the signal generator at 10MHz further increased 18dB the signal strength received (see section 5.3.4).
4. Carried out trials of higher frequencies (20 to 40MHz) for transmission in the laboratory tank.

6.3 Project applications

The applications of EM waves in seawater are mainly in the offshore oil and gas industries, oceanographic research and military. The navigation systems in ship will be improved to detect the large objects underwater. (e.g. large rocks or iceberg in sea) The underwater communication will benefit from this project. Diver to diver communication can be achieved using EM waves for communication. A communication network can also be set up between the autonomous underwater vehicles (AUVs) and the base station. AUV can receive instruction from the base station by EM waves within their range and then operate on its own to perform the task. AUV uses EM waves to detect nearby objects and manoeuvre in the sea for its own mission. After completing the task, it will move back to base station to upload the data and waiting for a new instruction.

6.4 Future work

The project can be improved by:

1. Designing and construction of a low noise amplifier in the receiver. This can increase the sensitivity of the receiver. Weaker signal can be detected and then amplified.
2. Noise cancellation technique is useful in dealing with weak signals, which is close to the background noise level. As the signal to noise ratio will be increased if the noise is reduced. Thus, the signal obtained will be clearer.

3. Different modulation like amplitude modulation, frequency modulation and amplitude shift keying modulation may be introduced to investigate the efficiency of the whole system.
4. The matching circuit can also be introduced in the receiver which can reduce the signal losses due to mismatch the antenna and the receiver.
5. Constructing a new transmitter that can be used to perform trials in real marine environment like in the Albert Dock with the new design of launching antenna in the tap water inside a container instead of contacting the seawater directly. So that results of the new design obtained from the real environment can be compared to the laboratory tank to make sure they are consistent.
6. The original DDS can only be operated up to 20MHz which cannot be used for higher frequency trials. So, a frequency tuning circuit for frequencies over 20MHz to 60MHz should be designed so that tuning of frequency can be done outside the transmitter without retrieving the transmitter from the seawater and opened it.
7. Using simulation software like High Frequency Structure Simulator (HFSS) and FEKO to model the antenna which will benefit for designing any new types of antenna in the future for optimising the efficiency of the system.

Chapter 7

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Appendix A

Published paper

J. Lucas and C. K. Yip, A determination of the propagation of electromagnetic waves through seawater, International Journal of the Society for Underwater Technology, vol 27, pp.1-9, 2007

Abstract

For the past four years detailed experiments have been carried out to investigate the propagation of electromagnetic (EM) waves between antennae in seawater in the MHz frequency range. The results have clearly shown that propagation is possible over a distance of 100m in a Liverpool Dock for frequencies in the range 1 to 5MHz using a 30W amplifier. The existing water/air/water model of propagation cannot explain this result.

Therefore a theoretical model is given in this paper to explain the result and to give a generalised solution. It is based upon the generation of EM waves by dipole oscillations of the water molecules within the antenna electric field. The model has explained all the features observed in detailed experimental results obtained in tank experiments with both tap and salt water, whose conductivity varies between 0.1 and 4S/m, as well as in trials within Liverpool Dock. Within the tank the received signal

in tap water increases with increasing frequency, whilst in salt water it decreases with increasing signal frequency. In general the signals in seawater are –55dB lower than in tap water. For each frequency the signal strength in seawater during propagation shows a rapid decrease in the vicinity of the transmitting antenna (near field) but only shows a slow decrease in the far field. The slow decay in the far field is attributed to a combined diffraction loss and an attenuation loss that increases with frequency. This results in the received signal exhibiting a resonant effect in the frequency range 10 to 20MHz for propagation in seawater for a distance of 100m. Lower and higher MHz frequencies are difficult to propagate because the received signal strength is comparable with the background electrical noise within seawater (-135dBm) when a 30W signal is transmitted.

1 Introduction

Submarines communicate through seawater by using the 3 to 30Hz ELF waveband. Transmissions in this wavelength can travel to a depth of around 122m at ranges over 6000 miles. The major problem with using ELF is the size of the required antenna system which covers several square kilometres and the required power (kWs). Furthermore, data transmission rate is extremely low allowing only simple messages to be transmitted and received. Higher electromagnetic wave frequencies (30Hz – 3kHz) have been researched in detail by Dunbar [1] who has shown that the signal amplitude (I) and frequency (f) are related by the skin effect depth (δ) as follows:

$$I = I_o \exp(-R/\delta)$$

where I_o is the emitted signal amplitude,

R is the transmission range

and δ is the skin depth which is given by

$\delta = 250/\sqrt{f}$ metres for seawater.

Propagation distances up to 100's of metres are possible but with low data transmission rates

For commercial applications the oil and gas offshore industry require signals in the MHz frequency range to be available so that high speed communications and images may be used to enable diver to diver and substation to platform communications to be undertaken. A literature search carried out with the help of DERA [2] has shown that such measurements are scarce. In an early review publication, Bogie [3] reported successful transmission ranges in San Francisco Bay at 7MHz for a distance of 460m at a depth of 76m. The research results of King [4] have been published in a series of papers on the design of sub-sea antennae. He clearly showed the rapid attenuation of the signal strength in the vicinity of the transmitter. Using these results Butler [5] undertook a theoretical analysis of propagation through seawater and concluded that at a frequency of 1.8MHz propagation was only possible with the antennae at a depth of less than 0.5m. This was achieved by partial propagation occurring through the atmosphere as shown in figure 1.

Because of this sparse information a detailed experimental programme of research has been undertaken. Detailed measurements taken over the past four years, within a European project EMCOMMS, have clearly shown that propagation of electromagnetic (EM) waves is possible in seawater and that there is a window between 1 and 10MHz through which EM waves can be propagated through seawater for distances greater than 100m. The purpose of this paper is to provide a basic model of this effect, which explains the experimental results taken in both a large testing tank and also in a dock environment. The advantage of using a testing tank is that it can be filled with either tap water or a range of salt water concentrations with conductivities varying from 0.01 to 4S/m to allow detailed analysis of the propagation model. Standard seawater has a conductivity of 4S/m

2 Measurements of the Propagation Through Water with Variable Conductivities

2.1 The Test Procedure

A polypropylene plastic testing tank whose dimensions were 2m (w) x 1.5m (h) x 2.5m (l) was available for the laboratory testing experiments. A wide variety of antenna constructions were used (single loop, dipole, folded dipole and multiple loops). The results are given in detail in the Final Reports of the EC Debye project [6], the EC EMCOMMS project [7], which were both coordinated by one of the authors (JL), and in two MSc theses by S. Saman [8] and S. Gresimidis [9]. All these results have shown the same trends so that coated double loop antennae of 320mm diameter were used to produce the summary results given in this paper.

The water in the tank was initially tap water having a conductivity of 0.02S/m. By adding salt, the conductivity could be increased, in stages, up to 4S/m, which corresponds to the conductivity of seawater. The antennae were attached to stand-alone stainless steel cylindrical tubes containing the electronics. The transmitter was battery operated and had no external electrical connections as can be seen in figure 2. The transmitter block diagram is shown in figure 3. The transmitter has a fibre optic link so that the battery power can be conserved. The optical link allows the batteries to be remotely switched on/off and also the voltage and temperature can be monitored. All the electronics were constructed in modular form on PCBs. An important module is the DDS frequency synthesiser, which generates square waves and allows the operating frequency to be electronically varied in the range 0.1 to 66MHz. The received signal was measured using an Anritsu hand held spectrum analyser (0.1 – 3MHz, type MS2711D) and the fundamental frequency measured.

Such a transmitter system was used to obtain the results in both the tank and in the Liverpool dock propagation trials.

The experimental technique was to measure the received signal as the distance between the transmitter and receiver is increased. There is initially a sharp fall in signal level within the near field but this levels out to provide a measurable far field signal.

2.2 The Tank Results

The centres of the antennae were placed 0.75m below the surface of the water. The results obtained as the separation was varied between 0 and 2m are shown in figures 4 and 5 for the transmitter frequency range of 1 to 66MHz and transmitter power of 20mW. Figure 4 is for tap water whilst figure 5 is for weak seawater conductivity

(1S/m). The received signals rapidly decreased with distance until a far field signal level is attained. For tap water the far field intensity increases as the frequency increases whilst for salt water there is a maximum far field at 25MHz. The received signal amplitude at 25MHz is approximately 30dB lower in salt water compared with tap water. As shown in figure 6 there is no substantial far field signal when the frequency is 1MHz in either tap or salt water. However, at 25MHz, as shown in figure 7, there exists a satisfactory far field with the signal being at least 30dB stronger in tap water. In figure 8 is shown how the received signal strength decreases as the conductivity increases up to 4S/m for a frequency of 25MHz.

Tank measurements with the conductivity at the seawater level of 4S/m are given in figure 9, which show that an optimum frequency of 4MHz is preferred with the far field strength reducing at both lower and higher frequencies.

2.3 Dock Results

Experiments were obtained within the Liverpool Dock with the antennae and electronic box suspended on floats between 2.5 and 3m below the surface of the water and the distance varied up to 100m.

Results within the Liverpool dock showed that distances up to 100m could be obtained using a 30W transmitter amplifier, as shown in figures 10 and 11. The signal has clearly shown the near field and far field regions.

At a distance of 4.7m at the start of the far field, the signal strength showed that there was a rapid fall off at signal frequencies below 1MHz in contrast to the results previously attained in the ELF region (Dunbar [13]). Although the signal strength at 4.7m was higher at 5MHz, for longer propagation distances 3 – 4MHz frequencies were preferred. It was observed experimentally that frequencies above 5MHz were more difficult to transmit a distance of 100m when using a 30W amplifier because of the closeness of the far field signals to the noise level intensity within the seawater. The results obtained were independent of the depth of the transmitting and receiving antennae in the water.

In figure 12 is shown the result of varying the antennae in a vertical distance within the dock. The results followed a similar pattern as was observed with horizontal water distances. There was a rapid attenuation of the signal followed by a far field region after a distance of 1m. The depth of the dock water limited the maximum depth attainable in these trials at 6m.

3 A Basic Theoretical Explanation of EM Wave Propagation

3.1 Introduction

The proposed theory by Butler [5] illustrated in figure 1 has not been observed in our results. For such a transmission path the received signal (I_1) at a frequency of 1MHz should be much higher than the signal (I_5) at 5MHz in both tap water and seawater. For an antenna depth of z from the surface the intensity at the surface decreases according to Maxwell's equation (see section 4.1), which is given by

$$I = Io \exp(-\alpha z)$$

with α_1 = -35 dB/m at 1MHz frequency

and α_5 = -78dB/m at 5MHz frequency.

For an antenna depth of 2m in seawater the ratio of intensities I_5/I_1 = -86dB at the surface prior to propagation through the atmosphere. From the results given in figure 10 the intensity ratio is I_5/I_1 = +20dB. Hence it is necessary to seek an alternative explanation. This has been based upon the production of EM radiation generated by the dielectric dipole water molecules and will be outlined in the following sections. The objective is to identify the dominant terms in the generation, transmission and reception of this radiation.

A basic seawater antenna consists of two metal rods coated with insulator within the electrically conductive seawater as shown in figure 13. When a voltage v_a is applied between the antenna rods, a lower voltage v_s is generated within the seawater. However, this voltage is quickly reduced to zero by electric current conduction within the seawater. The electrical conductivity consists of the conductivity of the seawater and the dielectric loss of the water molecules. The dielectric loss is generated by dipole oscillations within the water and it is this dipole radiation source that generates the EM waves for propagation through the seawater.

3.2 Equivalent Circuit of Antenna

The Effect of Water Conductivity

The antenna metal has been shielded from the seawater by an insulating coating material, which does not absorb water. Any voltage (v_a) applied to the antenna will be distributed across the insulator and the seawater. This is represented by three capacitors as shown in figure 14 and a voltage (v_s) appears across the seawater.

The voltages are initially related by

$$\frac{v_s}{v_a} = \frac{1}{2C_2 / C_1 + 1}$$

The values of C_1 and C_2 are as follows

$$C_1 = \frac{2\pi\varepsilon_0\varepsilon_{r1}}{\log(b/a)} \quad , \quad C_2 = \frac{\pi\varepsilon_0\varepsilon_{r2}}{\log(\mathrm{d/b})}$$

with $\varepsilon_{r1} = 4.2$, $\varepsilon_{r2} = 72$, $a = 2.5mm$, $b = 4.3mm$ *and* $d = 170mm$

Therefore $\dfrac{2C_2}{C_1} = \dfrac{\varepsilon_{r2}}{\varepsilon_{r1}} \dfrac{\log(b/a)}{\log(d/b)} = 2.48$ and hence

$$\frac{v_s}{v_a} = 0.287 \qquad (1)$$

Therefore there is a 71% loss of signal when generating the voltage within the water.

Furthermore the capacitance C_2 has a fast time constant due to the conductivity of the water so that this voltage quickly collapses and this greatly reduces the energy available to generate the transmitted EM wave.

3.3 Effect of Time Constant

The capacitance C_2 has a leakage resistance R_2 due to the conductivity of the water.

The voltage v_s within the water quickly collapses with a time constant τ.

$$v_t = v_s\, exp(-t/C_2R_2)$$

with $\tau = C_2R_2 = \dfrac{\varepsilon_0\varepsilon_r}{\sigma}$

The parameters for water are given in table 1 and show that the time constant in seawater is extremely short at 159ps compared with the value for tap water (35.8ns).

When a square wave voltage, as used in the experimental trials, is applied to the antenna having a time constant τ, it only creates an active signal (v_t) over the initial part of the signal period ($T = 1/f$), which generates an average value ($\hat{v}$) over the period T

$$\hat{v} = \frac{\int_0^{T/2} v_t dt}{T} = \frac{\tau v_s}{T}\left(1 - \exp(-T/2\tau)\right) = v_s f\tau\left(1 - \exp\left(-\frac{1}{2f\tau}\right)\right) \qquad (2)$$

Table 2 gives the calculated values for the average signal strength $\hat{v}$ emitted from the antenna for propagation within seawater. In the presence of seawater the signal attenuation is highest at low frequencies with a value of –82dB at 0.5MHz. For higher frequencies the signal strength increases with frequency. At 60MHz frequency the signal strength is still only –49dB. In tap water the signal is stronger and increases from –34.9dB at 0.5MHz to –1.9dB at 60MHz.

3.4 Effect of Dielectric Loss

The resistance R_2 is made up of terms representing conduction loss (σ) and dielectric dipole loss ($\omega\varepsilon^{11}$). It is the dipole dielectric term that provides the EM radiation for propagation through the water.

The electric power inserted into the water by the antenna is

$$\text{Power} = \frac{\hat{v}^2}{R} = \frac{\sigma_s \hat{v}^2}{L/A} = \frac{\hat{v}^2}{L/A}\left(\sigma + \omega\varepsilon^{11}\right)$$

where L and A are the length and cross-sectional area of the resistance path.

The fractional power (FP) within the dielectric dipole term is

$$FP = \left(\frac{\omega\varepsilon^{11}}{\sigma + \omega\varepsilon^{11}} \right)$$ and the fractional voltage is

$$\frac{v_i}{\hat{v}} = \sqrt{\frac{\omega\varepsilon^{11}}{\sigma + \omega\varepsilon^{11}}} \qquad (3)$$

where the dielectric constant (ε) equals $\varepsilon^1 + j\varepsilon^{11}$.

The values of ε^1 and ε^{11} are given by the Debye equation [10] as follows

$$\varepsilon^1 = \varepsilon\infty + \frac{(\varepsilon_s - \varepsilon\infty)}{1+\omega^2\tau^2} \quad with \quad \tau_r = 8.20\ 10^{-3} ns, \quad \varepsilon_s = 80 \ and \ \varepsilon_\infty = 3$$

$$\varepsilon^{11} = \frac{(\varepsilon_s - \varepsilon\infty)\omega\tau}{1+\omega^2\tau^2}$$

For $\omega\tau_{<<}1$

then $\omega\varepsilon^{11} = 24.92\ 10^{-8} f^2$ *with f in MHz*

3.5 Effect of Standing Waves

When power (P) is supplied to an antenna from a coaxial transmission line there is no reflected power if its impedance is equal to the characteristic impedance $Z_o = 377\Omega$. The voltage developed across the antenna is

$$v = \sqrt{2Z_o P}$$

If the antenna impedance is not equal to Z_0 then a standing wave is set up, which reflects power back to the source. The absorbed power by the antenna is equal to

$4S/(1+S)^2$, where S is the voltage standing wave ratio (VSWR) [11].

Hence the voltage generated at the transmitting antenna is

$$v_a = \sqrt{2Z_o P}\left(\frac{\sqrt{4S}}{(1+S)}\right) \tag{4}$$

3.6 Summary of Strength of the Transmitted Signal

The actual transmitted signal is made up of the four terms given in equations 1 to 4 as calculated in sections 3.2, 3.3, 3.4 and 3.5.

$$v_i = \left(\frac{v_s}{v_a}\right) x \left(\frac{\hat{v}}{v_s}\right) x \left(\frac{v_i}{\hat{v}}\right) x (v_a)$$

so that

$$v_i = 0.287 x f\tau\left(1-\exp\left(\frac{-1}{2f\tau}\right)\right) x \sqrt{\frac{\omega\varepsilon^{11}}{\sigma+\omega\varepsilon^{11}}} x \sqrt{2Z_0 P}\left(\frac{\sqrt{4S}}{1+S}\right) \tag{5}$$

where P is the power supplied to the antenna and S is the voltage standing wave ratio for the antenna. The VSWR can be made equal to 1 if the antenna impedance Z = R + jwL is matched to 50Ω.

By inserting the parameters from table 1, the following summary equations are obtained.

3.7 Signal Propagation in Tap Water within the Tank

Transmitted signal strength

$$v_i = 0.287x\frac{f}{27.92}\left(1-\exp\left(\frac{-14.0}{f}\right)\right)x\sqrt{\frac{24.92f^2}{2\ \ 10^6+24.92f^2}}x\sqrt{754P}\left(\frac{\sqrt{4S}}{(1+S)}\right) \quad (6)$$

The transmitter power (P) in tap water was 20mW (13dBm). The variation of the signal strength released by the transmitting antenna as a function of frequency is given in table 3 and figure 15. The signal strength increases from –59dBm at 0.5MHz to +15.6dBm at 60MHz when VSWR = 1

3.8 Signal Propagation in Seawater within the Tank

Transmitted signal strength

$$v_i = 0.287x\frac{f}{6289}\left(1-\exp\left(\frac{-3144}{f}\right)\right)x\sqrt{\frac{24.9f^2}{4\ \ 10^8+24.9f^2}}x\sqrt{754P}\left(\frac{\sqrt{4S}}{1+S}\right) \quad (7)$$

The variation of the signal strength released by the transmitting antenna as a function of frequency is also given in table 3 and figure 15. The signal strength at 0.5MHz when VSWR = 1 is –111dBm, which is 52dBm lower than in tap water. The signal strength increases with frequency but at 60MHz it is still 66dBm lower than in tap water.

The effect of the VSWR at the transmitter is also given in table 3. These VSWR have been experimentally obtained. This additional loss can be avoided by matching the antenna impedance to 50Ω, which is the internal impedance of the power source. At the receiver antenna the VSWR is 1 because the load is 50Ω.

4 Transmission Losses in the Dock

4.1 Transmission Loss in the Near Field

The signal generated within the water is by two conductivity terms. The conductivity term (σ) generates conventional antenna EM waves whilst the dielectric dipole term ($\omega\varepsilon^{11}$) generates dipole resonance radiation.

The signal loss in the near field is caused by the conduction resistance across the voltage developed by the antenna and hence the conductivity term (σ). There is no loss in the near field for the dipole radiation because it is developed in the water by the dipoles of the water molecules. There is therefore a rapid loss of signal of the conventional EM wave within the water and is referred to as the near field. Their amplitude is represented by Maxwell's equation as follows.

This near field attenuation follows Maxwell's equation with

$$E = E_0 \exp(-\alpha z)\exp j(wt - \beta z)$$

where $\alpha = \sqrt{\frac{w\mu\sigma}{2}} = -35\sqrt{f\sigma} dB/m$

and f is given in MHz and σ in standard seawater conductivity of 4S/m. Hence α increases with both frequency and conductivity.

These near field waves can only be propagated long distances at very low frequencies as shown in table 4 for standard seawater ($\sigma = 4S/m$) and discussed by Dunbar [1].

4.2 Dipole Propagation Losses in the Far Field

Dielectric dipole waves are propagated over longer distances because there is a much smaller rate of attenuation in the far field. The attenuation at a distance z between the transmitter and receiver is represented by

$$E = E_0 \exp(-\alpha z) x \frac{r}{2z}$$

where α = attenuation coefficient and r is the loop antenna radius. The term r/2z represents the diffraction loss.

From Maxwell's equation in a lossy dielectric medium we have

$$\alpha = \omega \sqrt{\mu \varepsilon^1} \left(\varepsilon^{11} / \varepsilon^1 \right)$$

and from Debye's equation in section 3.4 we have

$$\varepsilon^{11} / \varepsilon^1 = 49.6 \;\; 10^{-6} f$$

so that $\qquad \alpha = 9.29x10^{-6} f^2 \;\; f \, in \, MHz$

Therefore the signal attenuation is $\dfrac{E}{E_0} = \exp\left(-9.29x10^{-6} f^2 z\right) \; x \; \left(\dfrac{r}{2z}\right)$

4.3 Diffraction Losses

The signal power from a point source obeys a $1/z^2$ relationship. Therefore the signal received by an antenna of radius r is

$$\frac{P}{P_s} = \frac{r^2}{4z^2}$$

Hence for a distance of 100m and an antenna diameter of 0.35m the signal loss is –49dB. Therefore in order to propagate 100m in seawater in dock trials it is necessary to partially compensate for this diffraction loss by using a 30W (+45dBm) amplifier rather than the 20mW (+13dBm) amplifier used to obtain the tank experimental results given in section 2.1. With this arrangement the net signal loss by diffraction/amplification is now –17dB.

4.4 The Received Signal

The receiving antenna is identical to the transmitting antenna. Once the signal reaches the receiving antenna a voltage (v_i) will be induced into the metal rods

As shown in section 3.2 and figure 13 when a voltage v_a is applied across the antenna the signal in the water collapses so that only a fraction of the voltage (v_i) actually remains across the receiving antenna rods. This represents the received signal

$$\frac{v_i}{v_a} = 1 - 0.287 = 0.713$$

4.5 Results

The theoretical results for a propagation distance of 100m in seawater, when using a 30W amplifier, are given in table 5 and figure 15. The results show that it is only possible to transmit dielectric dipole EM waves for frequencies between 5 and 40MHz with the optimum transmission being between 10 and 20MHz. The maximum signal strength is –78dBm at 20MHz. This calculation confirms the experimental results shown in figures 10 and 11 for the frequency range 1 to 5MHz.

The noise level in seawater is of the order of –135dBm so that there is only the order of 40dB above the baseline available for irregularities in the transmission path such as the variation of seawater conductivity and temperature. This result confirms the EM propagation in seawater is possible at low MHz frequencies but can only be observed by careful experimentation.

5 Summary

The theoretical results for EM wave propagation in both tap water and standard seawater have been summarised in tables 3 and 5 and figure 15. The results show that only propagation within the rf frequency band is possible. The optimum propagation frequency observed experimentally was between 4 and 10MHz in both tap water and seawater.

The theoretical results for experiments in the testing tank using a +13dBm rf source are given in table 3 and figure 15. They are in general agreement with the experimental results given in figures 2 to 7. The far field signal is attributed to the generation of only EM dipole waves within the water. The theory and experiments show that the signal strength in tap water increases from –68dBm at 0.5MHz to +12dBm at 60MHz. For standard seawater (σ = 4S/m) the results are at least -55dB weaker than in tap water.

When evaluating transmission losses in seawater within the dock it is necessary to consider both propagation attenuation losses and diffraction losses. The results given in table 5 and figure 15 are for a propagation distance of 100m in seawater. The rf source was 30W (45dBm) and diffraction losses have been estimated as –49dB at 100m. The results show that propagation is possible for distances up to 100m provided the rf frequency is in the region of 10MHz. The maximum signal strength is –86dBm, which is only 50dB above the random background noise within the seawater.

There are many applications of EM wave transmission through seawater. Propagation distances of 100m and frequencies of 10MHz are suitable for transmitting video images between an AUV and a ship, between divers and from sensors to buoys. Therefore EM waves are able to provide a complementary role to acoustic wave propagation for sub-sea activities

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Tables

	Dielectric Constant ε_r	Conductivity σ	Time Constant τ
Seawater	72	4S/m	τ = 159ps
Tap Water	81	0.02 S/m	τ = 35.8ns

Table A1 The electrical properties of water

Signal Frequency MHz	Signal Amplitude (seawater) $\hat{v}/v_S$ x 10^4	Signal Attenuation in seawater dB	Signal Amplitude (tap water) $\hat{v}/v_S$ x 10^{-2}	Signal Attenuation in tap water dB
0.5	0.79	-82	1.8	-34.9
1	1.59	-76	3.6	-28.8
5	7.95	-62	17.9	-14.9
10	15.9	-56	33.6	-9.5
20	31.8	-50	53.9	-5.4
40	63.6	-44	72.0	-2.9
60	95.4	-40	78.0	-1.9

Table A2 The emitted signal strength via the antenna

Amplifier = 13dBm, Receiving Antenna Factor = 0.713 (see section 4)

Signal Frequency f MHz	Measured value of the Antenna VSWR	Measured value of the Antenna Signal Loss $\frac{\sqrt{4S}}{1+S}$ (dB)	Emitted Signal in Tap Water (dBm) (VSWR = 1) from equation 6	Emitted Signal in Seawater (dBm) (VSWR = 1) from equation 7	Emitted Signal in Tap Water with Antenna VSWR (dBm) from equation 6	Emitted Signal in Seawater with Antenna VSWR (dBm) from equation 7
0.5	26	-8.5	-59.0	-111	-68	-120
1	22	-7.8	-35.1	-99	-43	-107
5	14	-6.0	-19.0	-72	-25	-78
10	12	-5.5	-7.7	-62	-13	-68
20	9	-4.4	+2.5	-54	-2	-58
40	8	-4.0	+11.0	-51	+7	-55
60	8	-4.0	+15.6	-50	+12	-54

Table A3 The Emitted Signal Strength within the Tank

Signal Frequency	Signal Attenuation
f (Hz)	E/E_0 at 100m (dB)
1	-3.5
10	-11.0
100	-35
1000	-110

Table A4 Near Field Wave Attenuation

Propagation Distance z = 100 m.				
Signal Frequency f MHz	Attenuation Parameter αz	Signal Attenuation Exp $(-\alpha z)$ (dB)	Emitted Signal with 30W Amplifier (dBm)	Received Signal (dBm)
0.5	0	-0.0	-137	-137
1	9.29×10^{-4}	-0.0	-124	-124
5	2.32×10^{-2}	-0.2	-95	-95
10	9.29×10^{-2}	-0.8	-85	-86
20	3.72×10^{-1}	-3.2	-75	-78
40	1.49	-12.9	-76	-89
60	3.34	-29.0	-71	-100

Table A5 Propagation in standard seawater

Figures

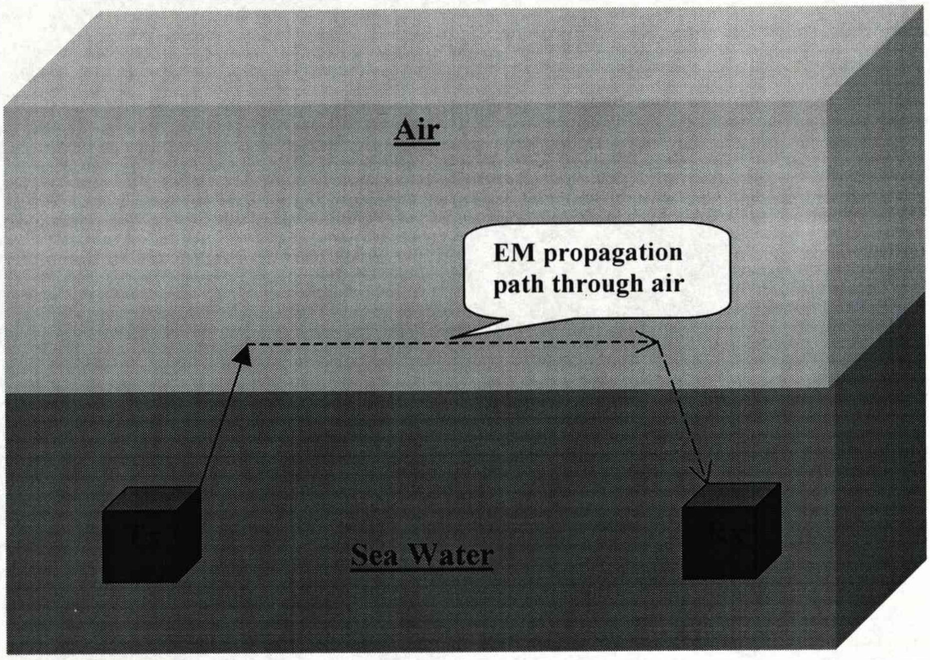

Figure A1 A Potential Propagation Path between Antennae

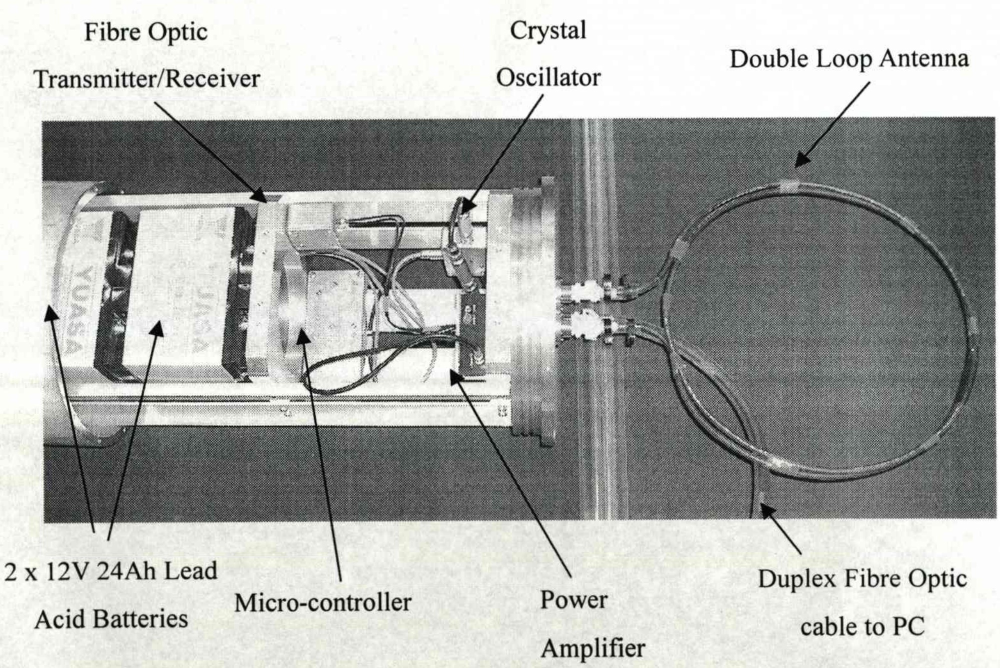

Figure A2 Transmitter Assembly

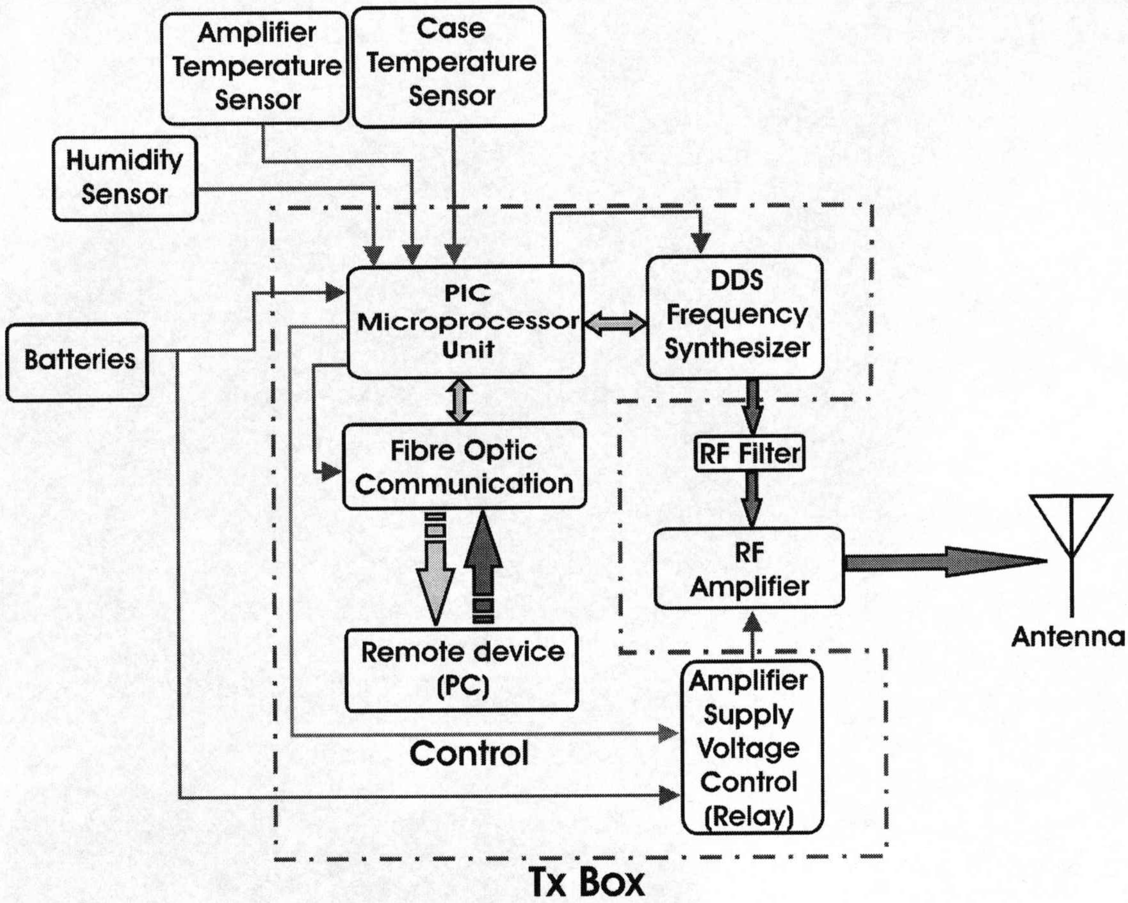

Figure A3 The Transmitter System

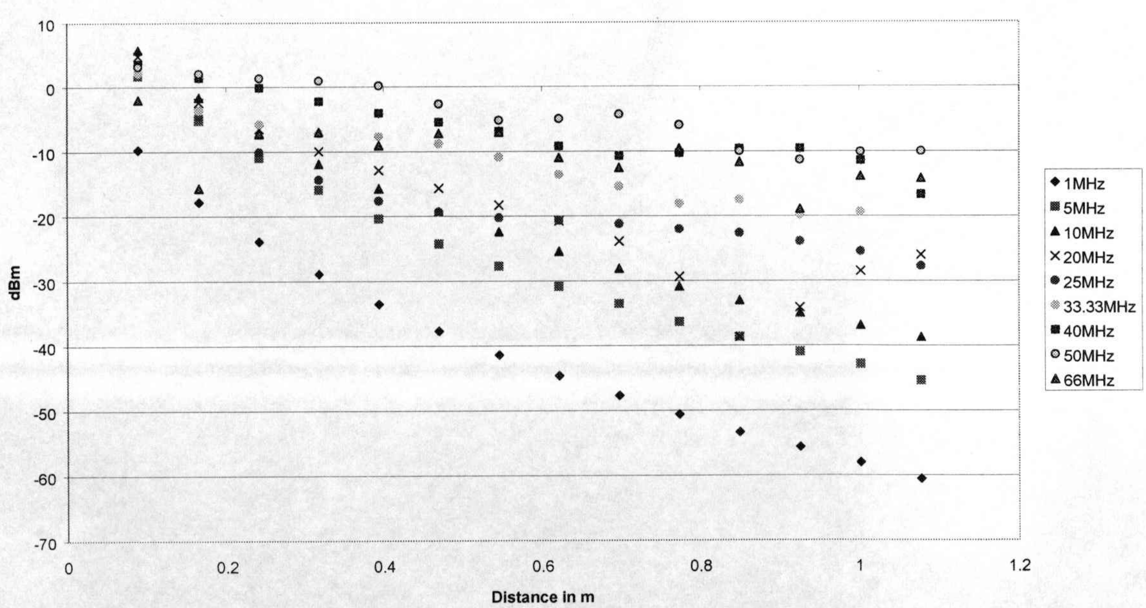

Figure A4 Loop Antennae (0.35m Diameter) in Tap Water, Tx is 13dBm

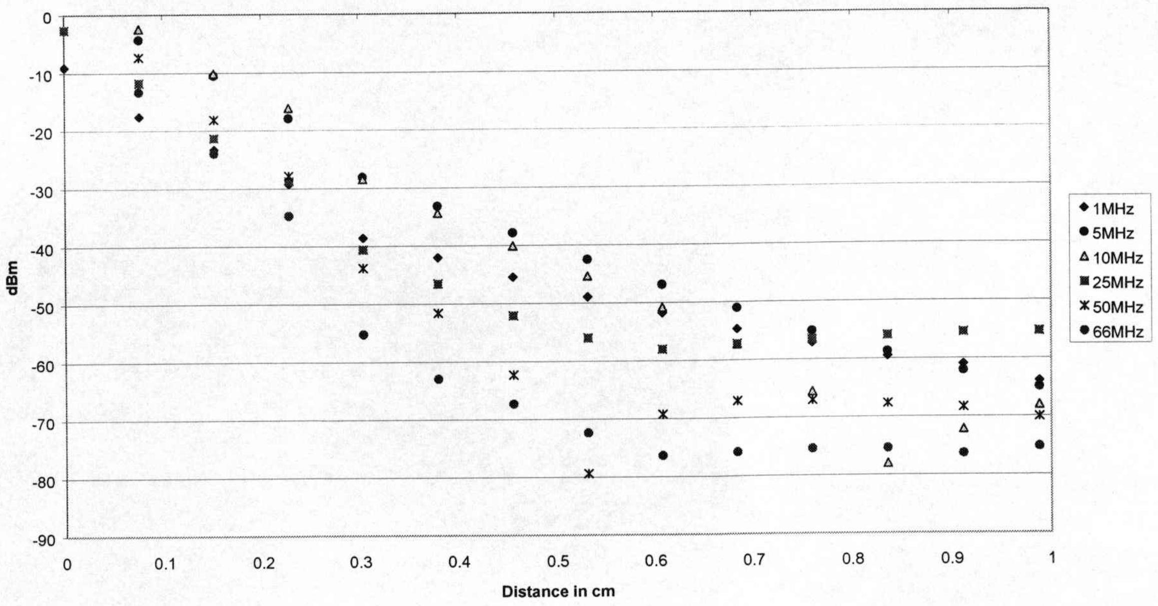

Figure A5 Loop Antennae (0.35m Diameter) in Salt Water (1S/m), Tx is 13dBm

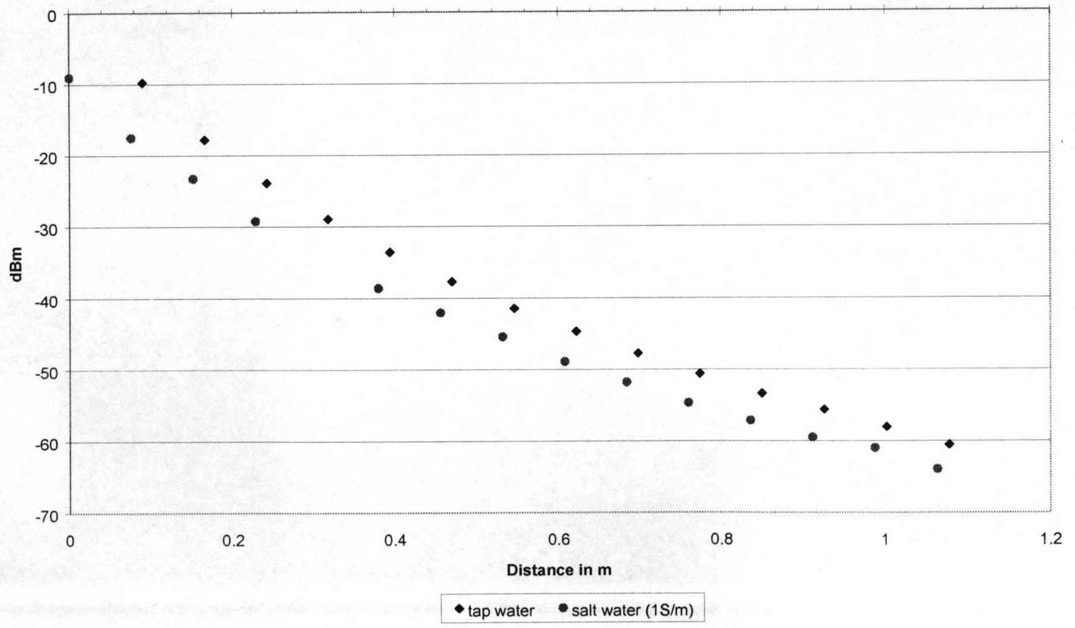

Figure A6 Loop Antennae (0.35m Diameter), frequency 1MHz, Tx is 13dBm

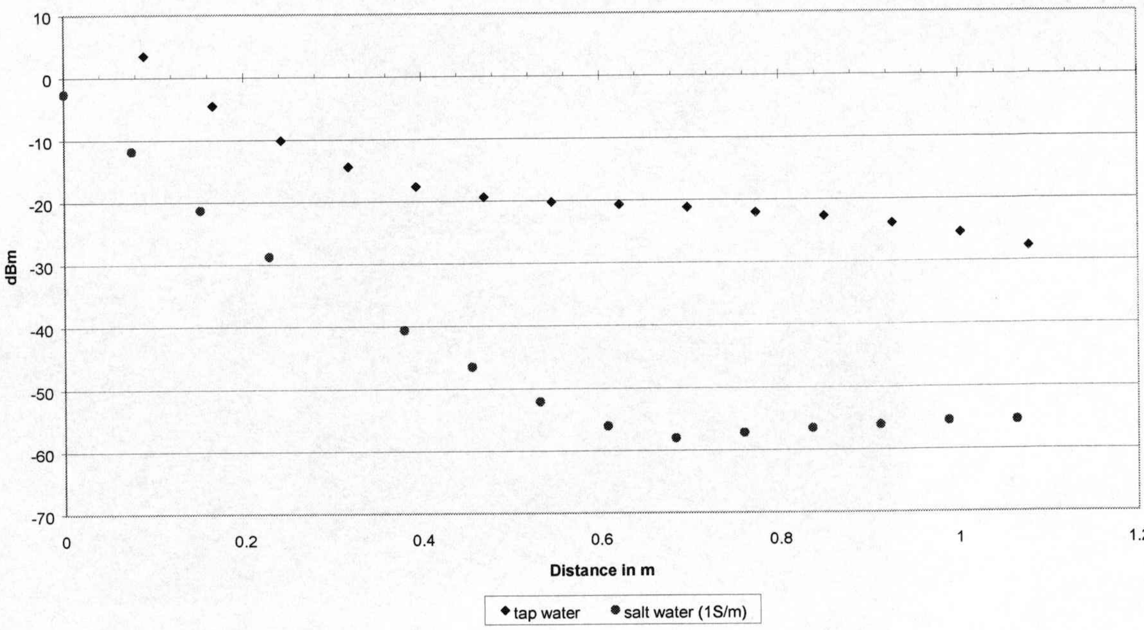

Figure A7 Loop Antennae (0.35m Diameter), frequency 25MHz, Tx is 13dBm

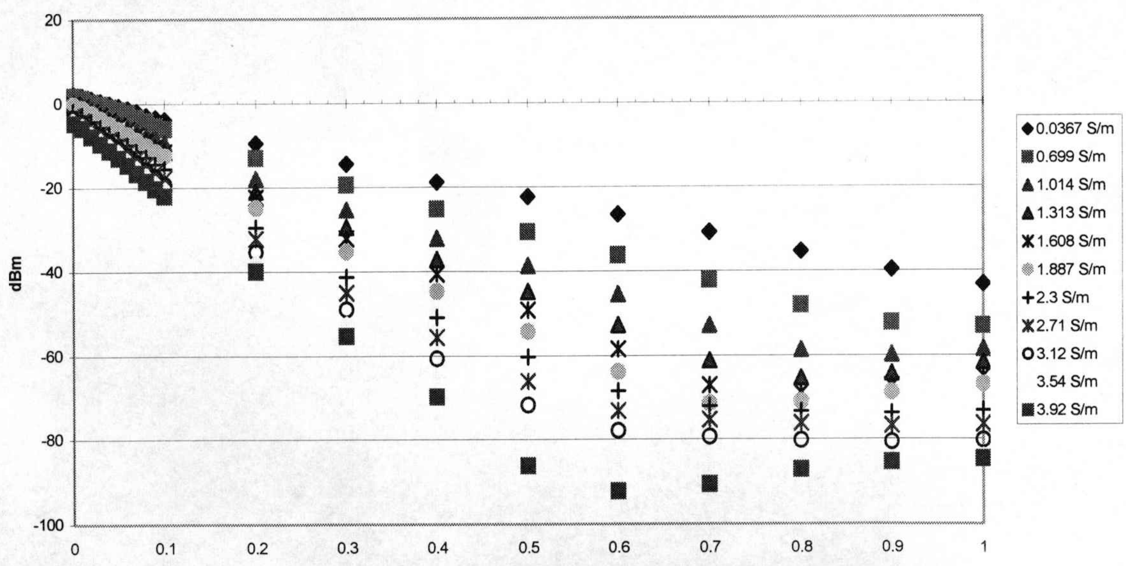

Figure A8 Results for 25MHz Dipole Antennae for varying salt concentrations, Tx with 13dBm

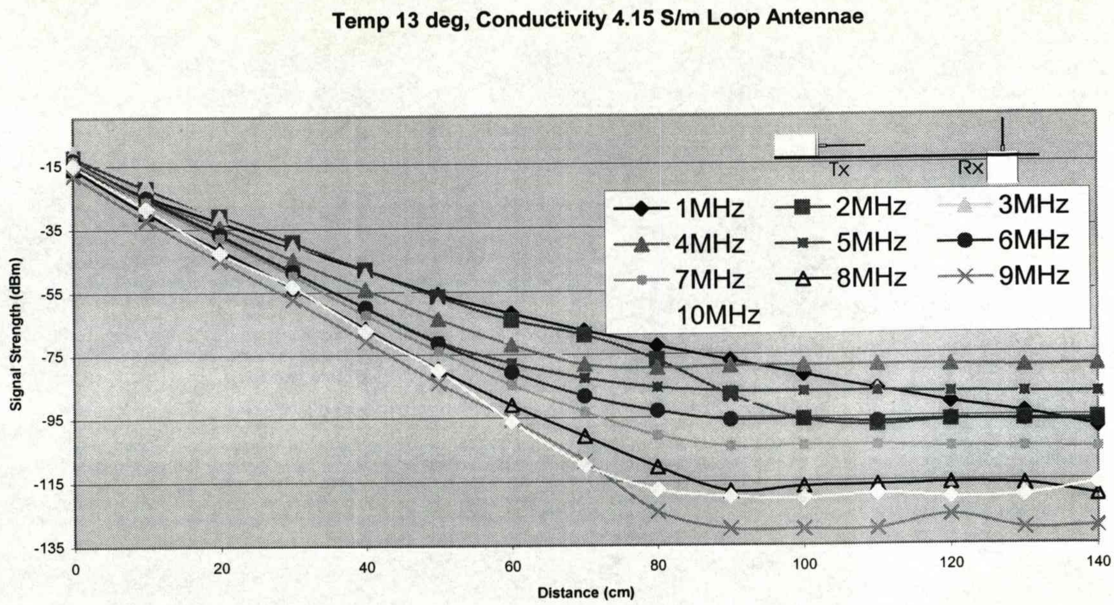

Figure A9 Signal Strength against distance varied Frequency in Tank

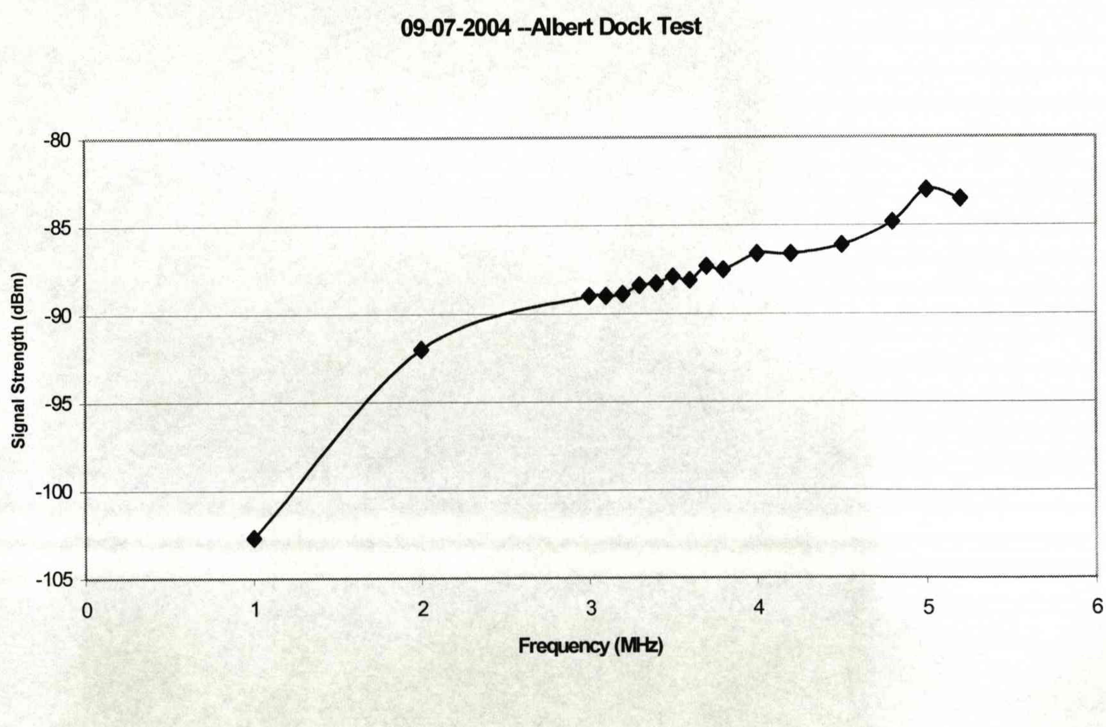

Figure A10 Frequency Scan Shakedown Test @ 4.7m Tx-Rx Separation - Conductivity: 3.65mS/m

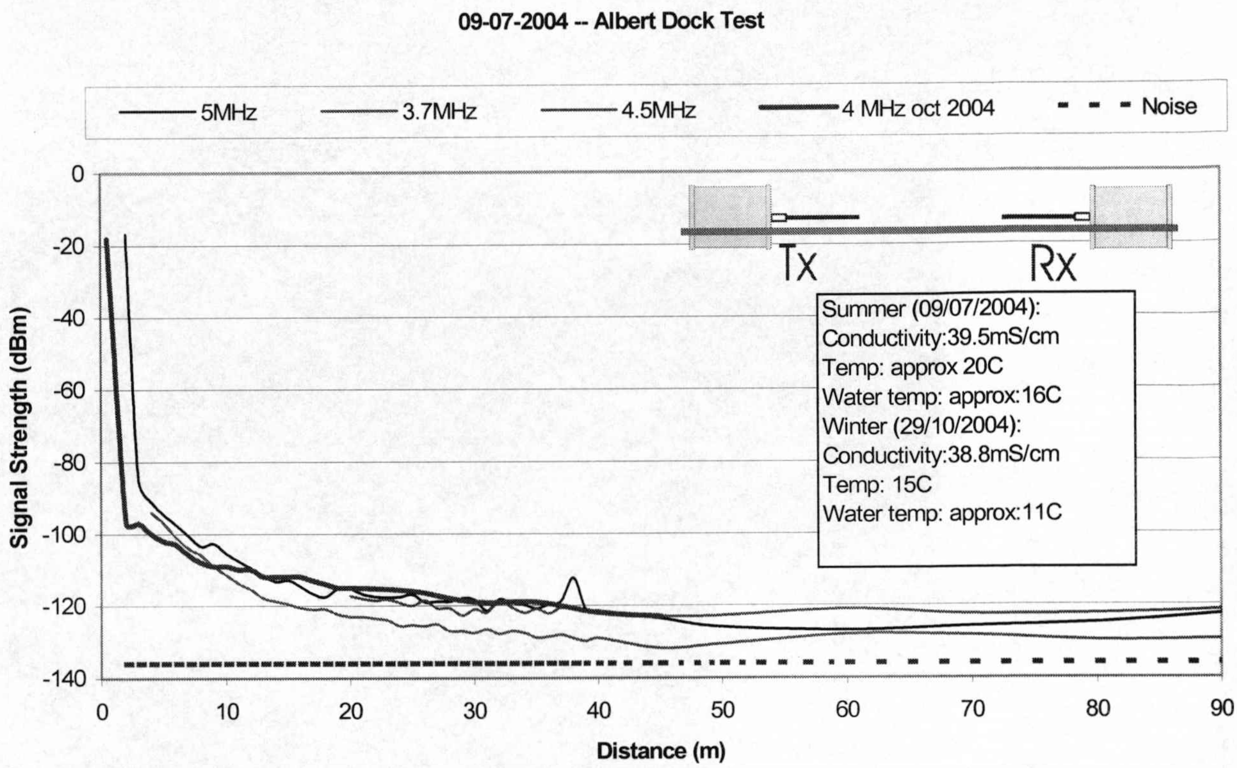

Figure A11 Signal Strength as a Function of Distance

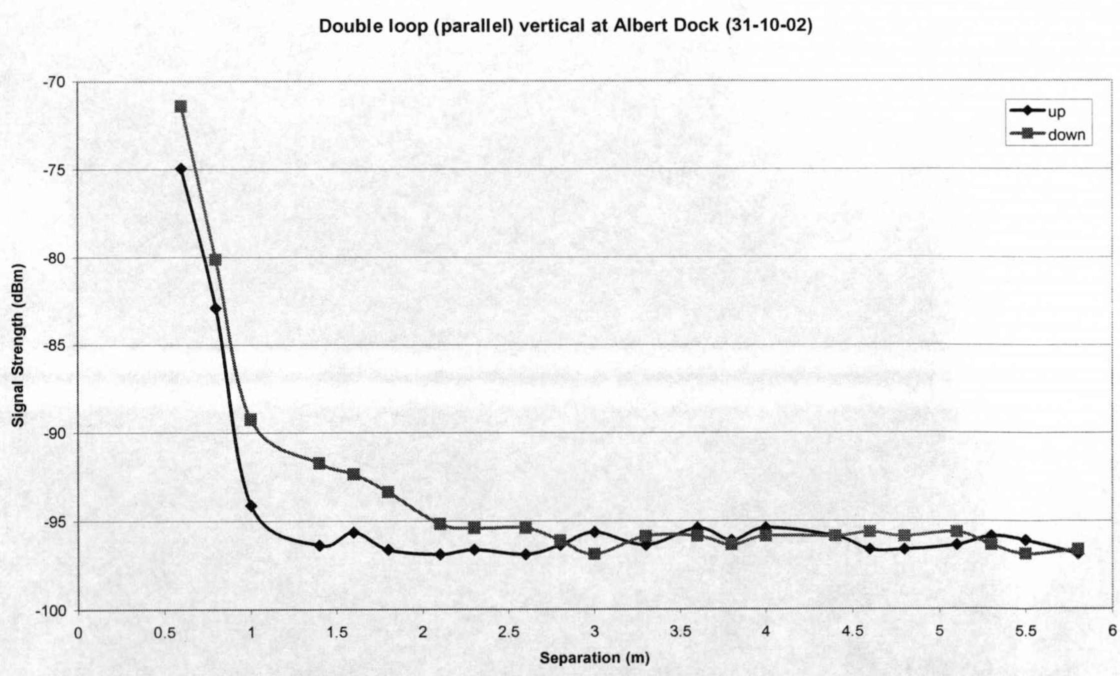

Figure A12 Signal Propagation between Antennae in a Vertical Direction in Seawater

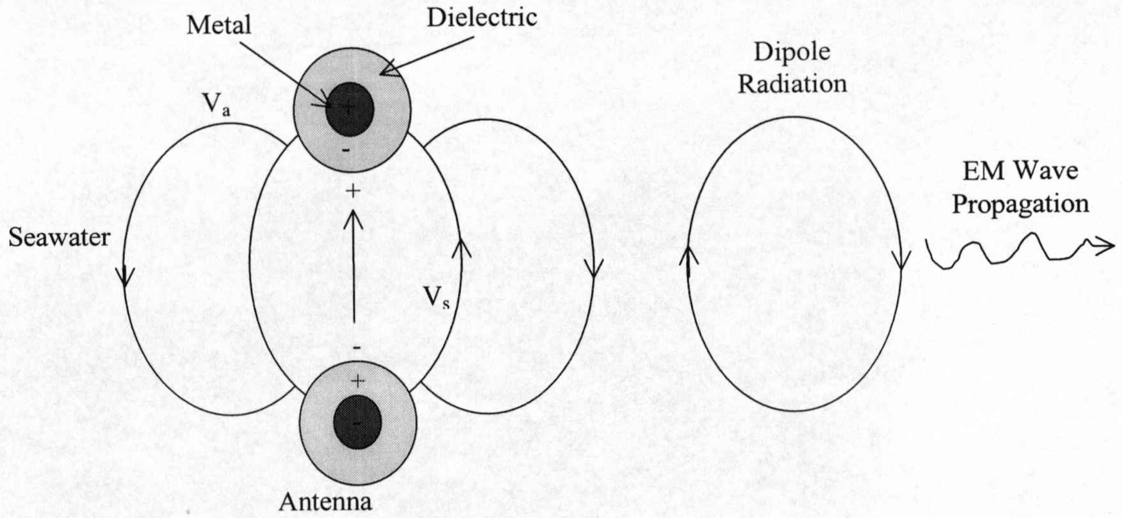

Figure A13 The Propagation Mechanism

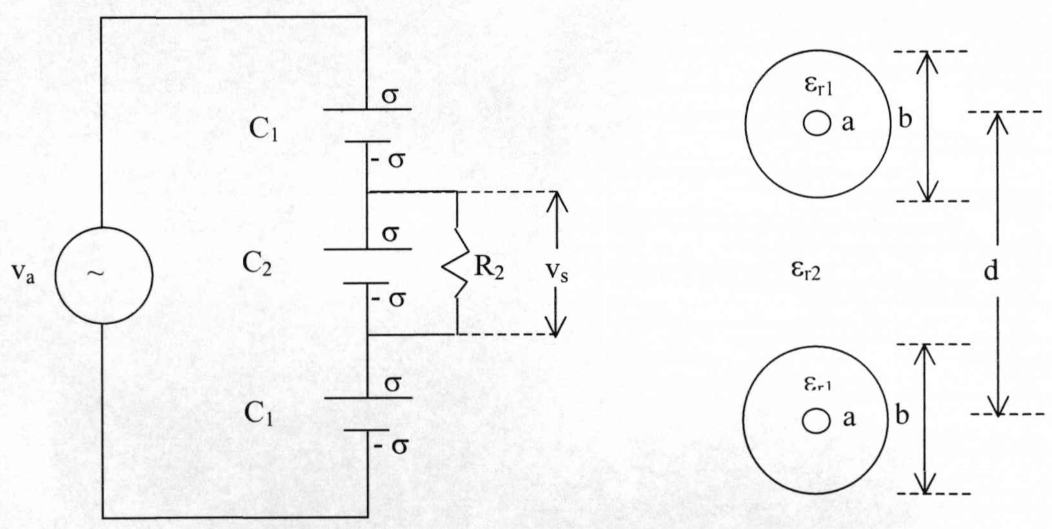

Figure A14 The Antenna Equivalent Circuit

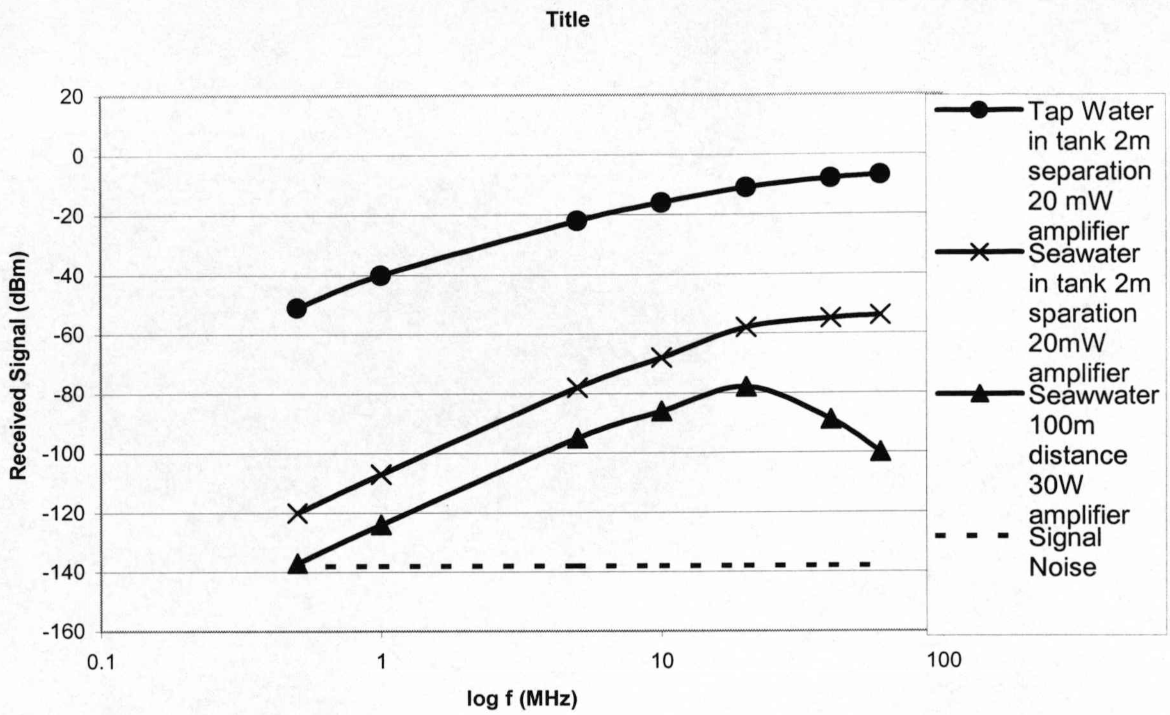

Figure A15 EM Wave Propagation in both Tap Water and Seawater

Appendix B

Circuit diagram of the electronics

B.1 Optical transmitter and receiver circuit diagram

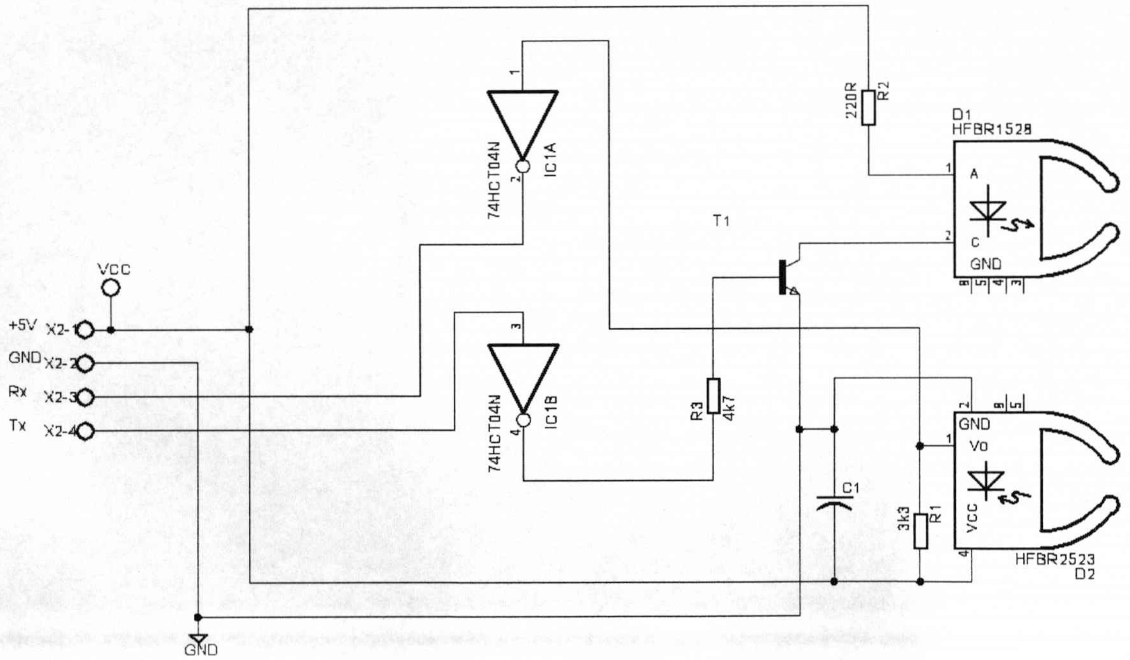

Figure B.1 Fibre optics transmitter and receiver circuit

B.2 Microcontroller Circuit diagram

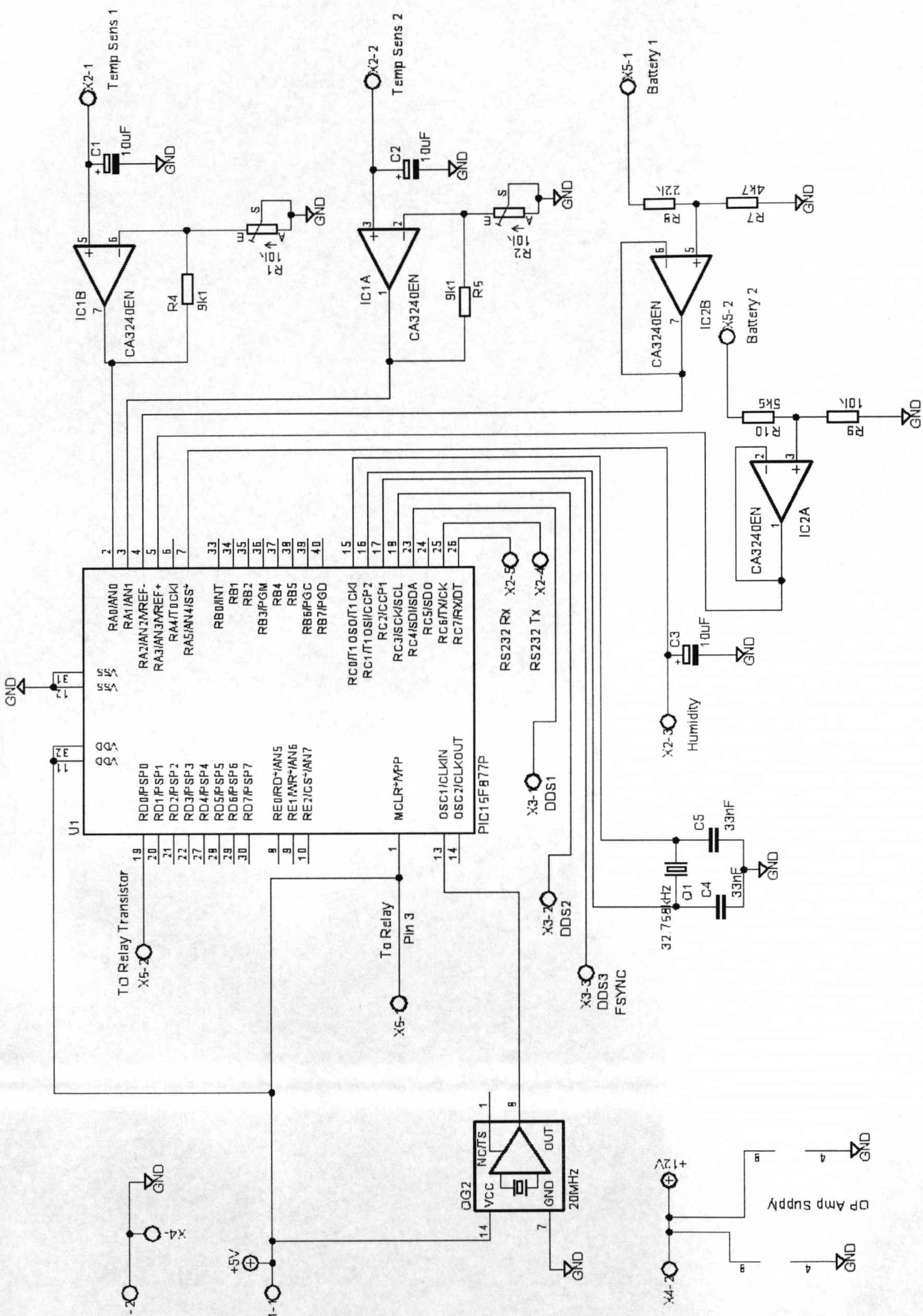

Figure B.2 Main circuit with microcontroller

B.3 DDS and LNA circuit diagram

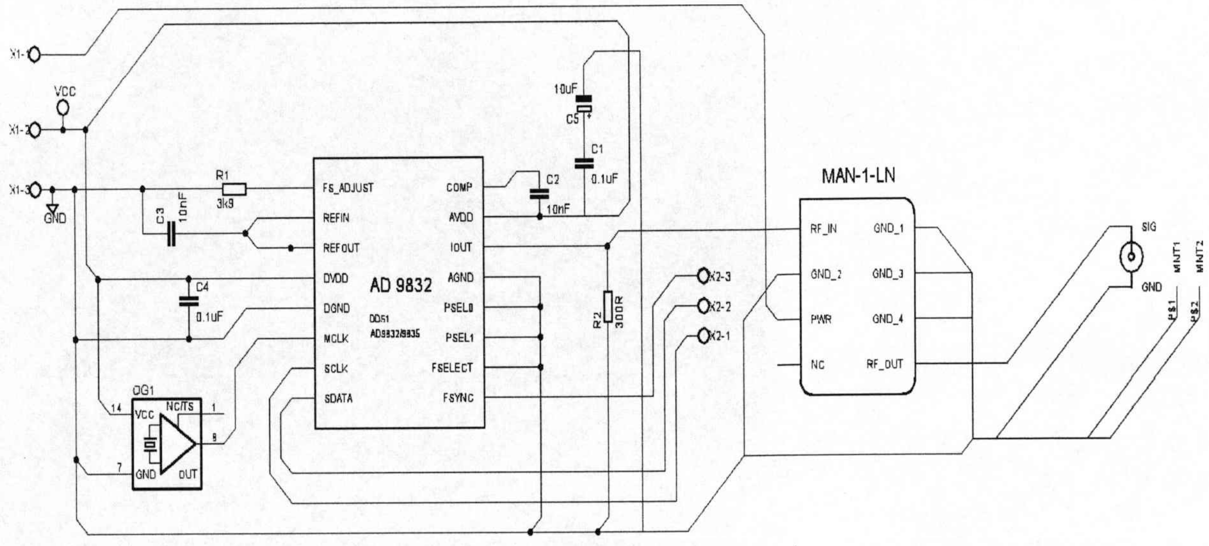

Figure B.3 DDS and LNA circuit

B.4 Voltage regulator circuit diagram

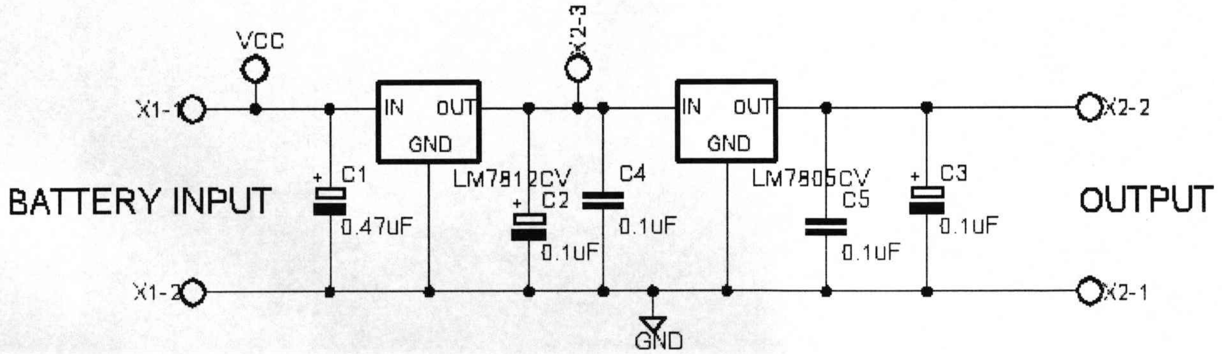

Figure B.4 Voltage regulator circuit for the power supply

B.5 Relay switch circuit diagram

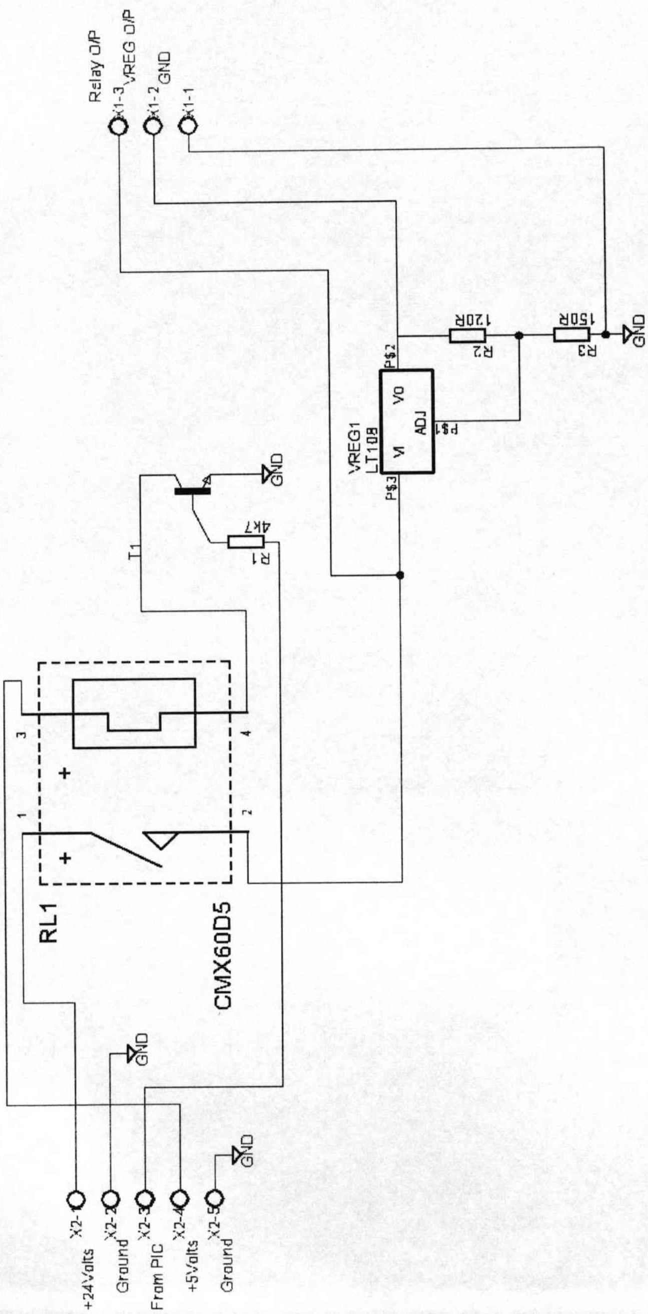

Figure B.5 Relay switch circuit